REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL 01 Oct 94 TO 30 Sep 95

4. TITLE AND SUBTITLE
REAL-TIME SENSING OF HUMAN-BODY SEGMENT POSITION AND ORIENTATION USING INERTIAL GUIDANCE METHODS & MICRO-MINIATURE TECHNOLOGY

5. FUNDING NUMBERS
F49620-94-C-0085
STTR/TS
65502F

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AFOSR-TR-96-0052

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19960220 026

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
(U)	(U)	(U)	(U)

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
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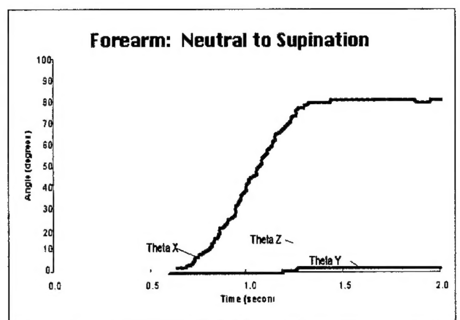
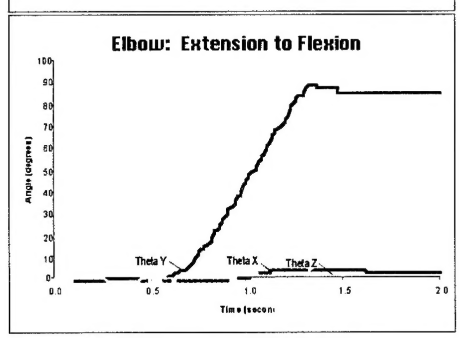
F49620-94-C-0085
Human Performance Measurement, Inc.
Final Report.

Real-Time Sensing
of Human Body Segment Position and Orientation
Using Inertial Guidance Methods
and Microminiature Technology

STTR Phase I Final Report

Contract Number: F49620-94-C-0085
Contract Period: 1-Oct-94 to 30-Sep-95





Prepared for:
Air Force Office of Scientific Research

Prepared by:
Human Performance Measurement, Inc.

30 November 1995

ABSTRACT

In this Phase I project, the feasibility of a compact completely body-worn and wireless means for sensing and communicating a human's position and body segment orientation in 3D space was demonstrated. The "total human"-"total system" approach introduced emphasized: (1) the study of human motion characteristics, (2) the human factors of such systems, and (3) exploitation of rapidly evolving base technologies (e.g., inertial guidance and earth magnetic field sensors, wireless local area networks, low power electronics, and rechargeable batteries). A system concept called the Human Position and Orientation Sensing System (HPOSS) was specified. With reference to Global Positioning Systems, we have coined the term *Local Position and Orientation Sensing System (LPOSS)*, of which HPOSS is a particular type. HPOSS consists of five multiple body segment sensor units (MBS-SUs; two arms, two legs, and one torso) and a single base unit (to be produced in 1,3, and 5 channel versions). This set allows for combinations that serve a wide range of applications cost effectively. The base unit communicates the requisite data via serial interface in a unique format intended to provide a standard for a new generation of high fidelity human-computer interfaces. Prototypes of selected subsystems were prototyped, tested, and demonstrated in laboratory conditions. Prototypes using both magnetic and inertial sensors were tested. Results indicate that sensor data for multiple body segments can be reliably collected over modest durations (for inertially based sensors), interpreted in terms of three dimensional position and orientation for those segments, and communicated to a base unit in real-time with enough accuracy for many applications. Numerous applications in government, education, medical, business, and entertainment sectors were identified; HPOSS is especially well-suited to fill virtual reality needs. A multifaceted approach to commercialization of the products is proposed that includes military and medical components. In Phase II, we propose to fully develop a first generation product set.

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List of Acronyms, Abbreviations, and Terms

DOF	Degrees Of Freedom
GUI	Graphical User Interface
HCI	Human-Computer Interface
HGI	Human-Graphical Interface
HPI	Human Performance Institute
HPM	Human Performance Measurement
HPOSS	Human Position and Orientation Sensing System
LPOSS	*Local* Position and Orientation Sensing System
MBS-SS	Multiple Body Segment Sensing System
SICU	Sensor Interface and Control Unit
UTA	University of Texas at Arlington
VR	Virtual Reality

1.0 Introduction

Film editors work toward the goal of creating a visual presentation that keeps the viewer's attention on the story and not the editing techniques. Similarly, human-computer interface (HCI) designers work toward the goal of making the computational capabilities of computer systems easily accessible to the user in a manner that keeps the user's attention on the task being performed and not on the features and operation of the user interface. HCI advances, illustrated in Figure 1, are improving the fidelity, bandwidth, and level of human-computer communication channels.

The use of graphical representations, window systems based on a desktop organization metaphor, and direct manipulation concepts have been combined to produce user interfaces that eliminate many of the barriers (arcane language, inflexible syntax, and screen navigation via keyboard to name a few) that inhibited efficient human-computer communication in the past. Arguably, the present ubiquitous reliance on computers for performing business, scientific, engineering, and personal tasks has been realized because these HCI advancements allowed users to readily interact with computer environments using communication skills already acquired in performing everyday tasks without computers. Virtual reality (VR) offers the potential to dramatically further enhance the fidelity, bandwidth, and level of the human-computer communication channel; moving the user toward a more flexible, natural, and powerful role that allows a seamless active participation in the operation of the task the user is using the computer to perform.

The potential range of tasks and disciplines to which VR can be applied to improve utility is broad. In consequence, VR technologies are being developed and integrated into a wide variety of human-machine systems at a rapidly increasing rate. Still, realizing VR's potential requires significant advances in real-time sensor, display, feedback, and control technologies. Many applications of VR will require the system and user to have reliable real-time data on the position and orientation of the user's own body and other humans, machines, or objects with respect to the virtual environment. The lack of this sensing and communication capability will severely limit the utility of VR for many applications. In addition, the psychology and physiology of human behavior in response to the use of these technologies and the magnitude of operational performance benefits that can be obtained need to be investigated.

The purpose of this project is to develop a real-time human position and orientation sensing system (HPOSS) that uses modular component technologies assembled into interacting sensing units for major body segments. The purpose of HPOSS is to enhance the fidelity, bandwidth, and level of the human-computer communication channel.

1.1 System Concept

The HPOSS concept is illustrated in Figure 1. We have defined a whole-body, total-system, modular, human-factored approach to HPOSS design and development . Key elements of our approach are: (1) reliance on an inertial sensing approach, (2) use of wireless data links between the human and computer, (3) use of battery powered systems, and (4) consideration of the "total system" and "total human" throughout design of all elements.

In particular, the HPOSS concept was motivated by analyses which demonstrated that an inertial approach to sensing position and/or orientation of a human and/or his or her body segments held distinct conceptual advantages over any other approach in use or that could be contemplated. The specific problem was generalized and described as one of Local Position and Orientation Sensing, which has distinctly different problems compared to global positioning and navigation systems in which inertial schemes have been used. Most importantly, demands on absolute speed and accuracy are signficantly greater. HPOSS is thus a specific realization of LPOSS.

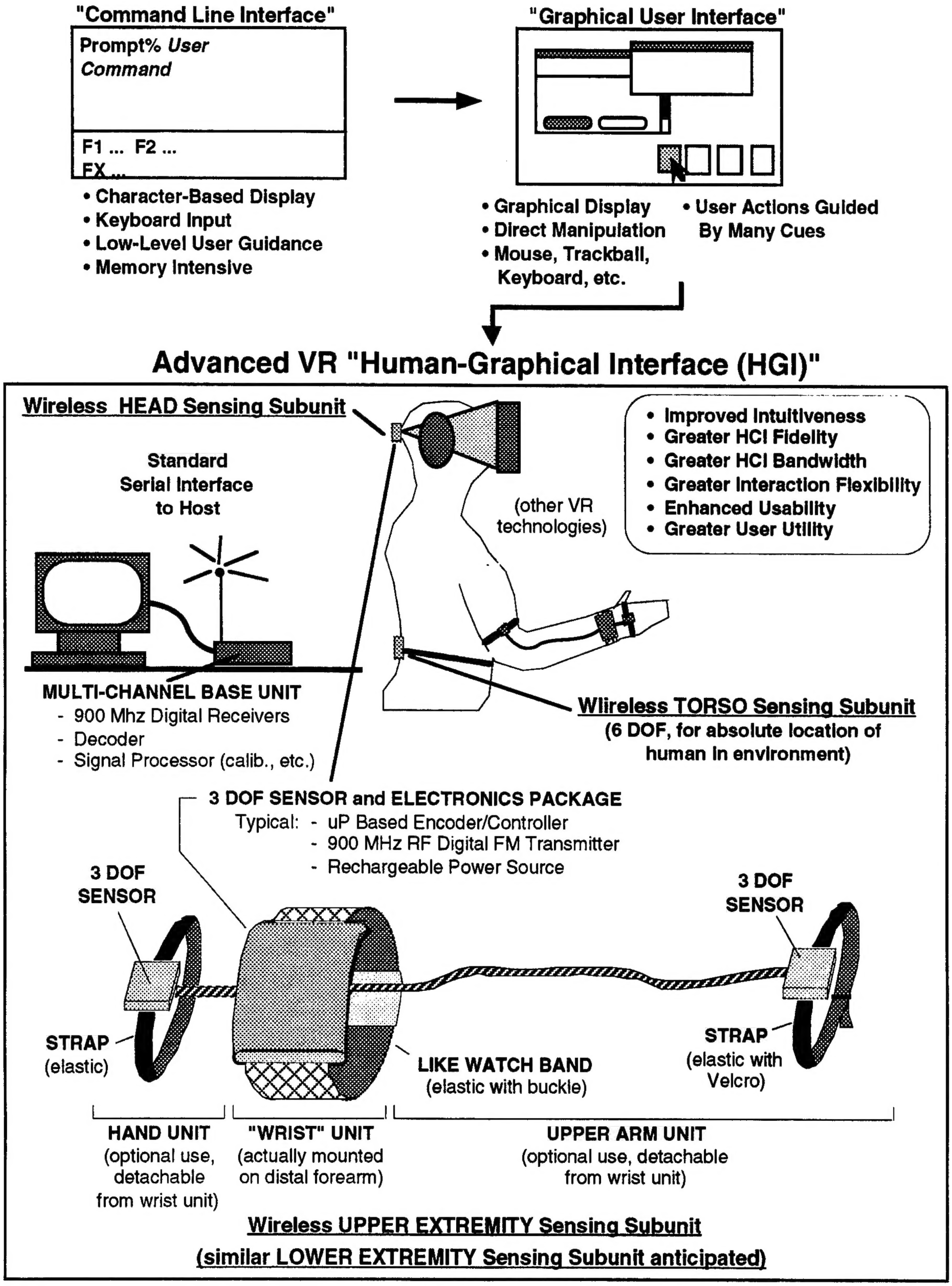


Figure 1. HPOSS system concept (as per Phase I proposal) supporting the evolution of an advanced Human Graphical Interface (HGI).

1.2 HPOSS System Design Overview

The HPOSS system design approach is driven by and derived from consideration of issues in three areas. The state of the art of available and emerging technology is not identified as a separate area of consideration because issues in each of the three areas are evaluated in the context of technology capability in near and far terms.

Total-Human and Total-System Approach: We are working toward developing a *total sensing system* solution for the *total human* which we have dubbed the Human Position and Orientation Sensing System (HPOSS). The concept derived from this approach is that of a family of modular units for different segments of the body (e.g., arm, leg, head) which communicate via digital RF links and are powered by rechargeable sources. These units are called Multiple Body Segment Sensing Subsystems (MBS-SSs). Figure 2 illustrates this total-system level concept. Each MBS-SS in the family consists of assemblies of more basic generic functional units.

The communication and interpretation of data for each MBS-SS and unit is envisioned to be standardized for the total body. From this "total-human and total-system" perspective, the design issues include: (1) system-level packaging and configuration options, (2) sensor technology evaluation, selection, and system design, (3) standard conventions and representations for degrees of freedom of the total human, (4) standardized, robust software interface methods that would allow use of HPOSS in various configurations (i.e., incorporation few or many degrees of freedom) and in different applications with relative ease.

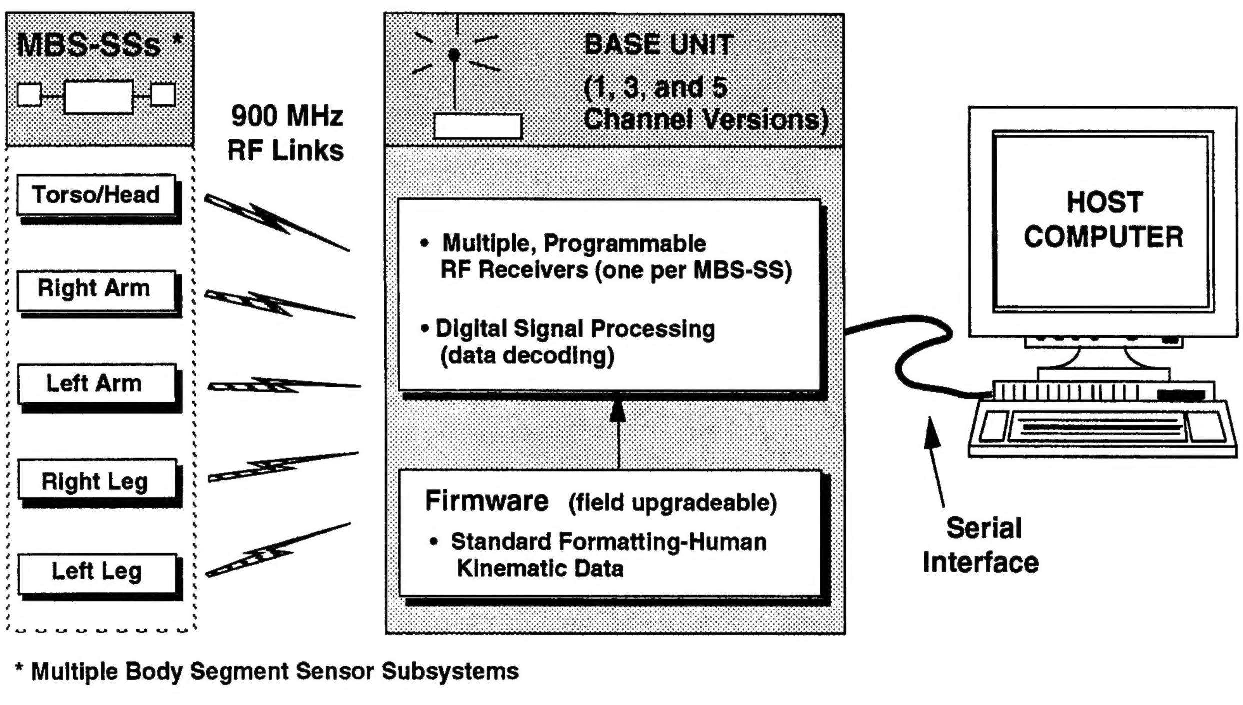
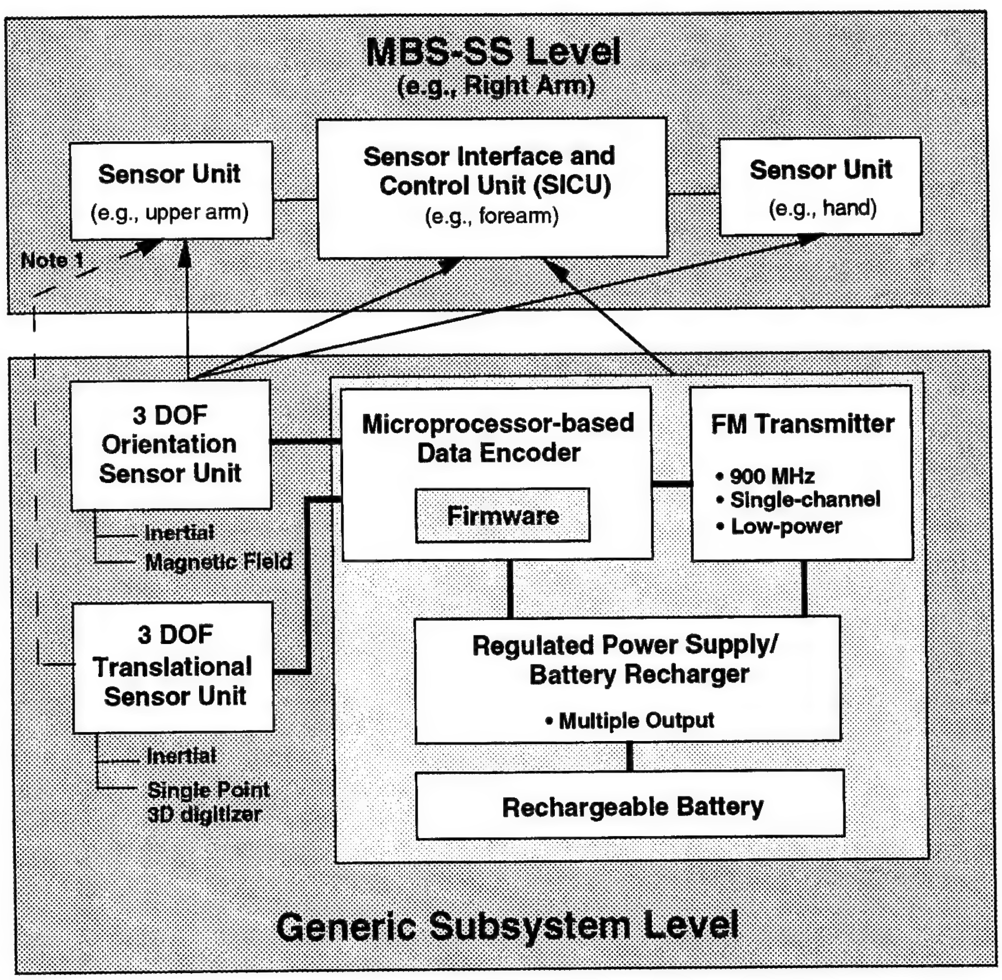


Figure 2. HPOSS Total-System Concept: Major Components of HPOSS include: (1) Multiple Body Segment Sensor Subsystems (five generically similar but distinctive models), and (2) the Base Unit. One additional component (the Single Point, Real-Time 3D Digitizer) is not shown, but is also considered to be part of the HPOSS package as a temporary substitute for an inertial position (e.g., translation) Sensor Unit.

Modularity of Design: HPOSS design uses three levels of modularity: (1) total system, (2) major subsystems called Multiple Body Segment Sensing Subsystems (MBS-SSs), and (3) the major components of MBS-SSs called units which incorporate generic functionality. Modularity of design allows us to flexibly analyze and design different packaging and configuration alternatives and to optimize the use of various generic functional units across different body segments and measurements. These optimization issues include: (1) What and how many components are used within a unit (e.g., the number of sensors needed for each sensor subsystem)? (2) How should generic functional units be partitioned and fabricated?, and (3) What units should be combined to form a MBS-SS for a given body segment or combination of segments?

Figure 3 illustrates the relationship between the generic unit and MBS-SS levels. Of the several critical base technologies, the sensor technology offers the most design options at present, as well as the most difficult performance tradeoff decisions. Options exist in two broad categories: (1) inertial and (2) magnetic field (specifically, use of only the earth's magnetic field; i.e., no artificially generated fields are used). Within these broad categories, alternatives available in the form of commercial components (modules and integrated circuits) for use in the sensor units have been investigated. Technology alternatives for sensor units are depicted in Figure 3.



Note 1: 3 DOF translational sensor unit is incorporated in head/torso MBS-SS only. Single point, real-time 3D digitizer option is completely external to MBS-SS.

Figure 3. Relationships among generic units and MBS-SSs

Human-Factored Approach: By taking a total-human approach from a biomechanical perspective, we are able to better quantitatively characterize sensor requirements and evaluate options. Of equal importance in our opinion (and perhaps of increasing importance as base sensing technology matures), this also forces us to address system design issues not directly associated with sensing *per se*, such as standards for communicating total human body segment orientations. Given the large number of degrees of freedom and intrinsic complexities of communicating the relative orientation between two bodies in three dimensional space, the latter should not be underestimated although it is frequently overlooked or avoided by considering only a single sensor system attached to a single body segment (e.g., the head).

With regard to quantitative factors directly related to predicting sensor performance in the intended application (i.e., human posture and motion), we have identified the following factors:

- weight and size of subunits and units appropriate for different segments
- speeds, accelerations, and ranges of motion associated with each body segment
- number of degrees of freedom needed for each body segment
- accuracy needed for each body segment
- orientation, position, and movement relationships and dependencies among different body segments.

Our development and transition approach provides for modular substitution of current and emerging technology and for a whole body integration that can meet the needs of future applications and accommodate upgraded technology gracefully using a plug in design concept.

1.3 Significance of HPOSS Technology

The HPOSS will provide the needed sensing and communication capability that currently severely limits the utility of implementing virtual reality and advanced human-computer interaction techniques for many applications. By obtaining, transmitting, and interpreting reliable, real-time data from users' natural body movements, HPOSS can improve a broad range of tasks. These improvements include the ease with which tasks are learned and performed, and the performance of tasks for which information on human movement is communicated as feedback to other users. In addition to the enhanced naturalness of the interaction, HPOSS also provides HCI benefits in terms of flexibility and remote operations capabilities. Remote interaction offers an enormous leap of potential in the methods under which information from the user is obtained and the applications to which it can be applied.

The available and validated technologies together create an exciting capability for interacting with digital information systems with minimal body intrusion and maximal motor freedom. This capability moves the point of interaction from the mouse and keyboard to the human body itself. Allowing the real-time movement of the body to become a graphical representation of user input that feeds and directs human interaction with computer software. HPOSS technology will satisfy this one well-defined general need which is directly applicable to many VR applications including:

- command and control workstations,
- training systems (e.g., surgery, maintenance),
- rehabilitation (e.g., motion analysis, performance measurement, biofeedback during therapy),
- use of artificial proprioception for use on assistive device technology, telerobotics, and equipment operation,
- multimodal feedback systems,
- HCIs for the disabled,
- interactive entertainment.

2.0 Technical Objectives

The overall project goal is to develop and commercialize a comprehensive (i.e., total human) and complete (i.e., total system) Human Position and Orientation Sensing System (HPOSS). The project is designed to accomplish this goal in three phases. In Phase I, we moved a significant step toward this goal by clearly demonstrating the technical feasibility and commercial potential (1) for transferring the required base technologies into body segment sensing units, (2) for communicating this sensor data, and (3) for computing joint angles from this data. Our Phase II objectives and work plan combined with our Phase III plans constitute the remaining steps to be accomplished. These objectives and plans are consistent with our pre-Phase I vision and define a systematic and in-place product development and commercialization strategy for achieving our overall project goal.

2.1 Phase I Objectives

The overall objective for Phase I was to evaluate and demonstrate the feasibility and benefit of transferring unique technologies for real-time sensing and transmitting of the position and orientation of selected points on the human body in three-dimensional space from the laboratory into well-engineered product packages that meet the needs of future government and commercial sector HCIs. The specific objectives and rationale for Phase I are listed in Table 1.

Table 1. Specific Phase I Objectives

Obj.	Description	Additional Description/Examples/Rationale
1	Assess technology options.	• Sensor technologies • Transmitter technologies • Receiver technologies
2	Assess market applications and requirements (government and commercial).	• High-fidelity human interfaces to complex systems • Human-computer interfaces for persons with disabilities • Rehabilitation (e.g., motion analysis, performance measurement, biofeedback during therapy) • Computer-assisted training (e.g. surgery, maintenance) • Artificial proprioception for use in assistive device technology and robotics • Emerging applications in entertainment and recreation.
3	Develop/evaluate candidate subsystem designs.	• Draw from related work

4	Determine the optimal human interface packaging of the technology elements.	• For example, compare (a) one sensor unit with transmitter and power source per segment to (b) one transmitter and power source per multiple sensors.
		• Assess:
		  • performance of packaged units.
		    • accuracy
		    • operating region
		    • endurance (for battery powered options)
		    • operating environment restrictions
		  • portability
		  • reliability
		  • technology maturity
		  • cost

5	Evaluate and demonstrate system level feasibility and operational user utility for typical applications.	• Integrate subsystems into two proof of concept prototypes. Integrate prototypes with selected off-the-shelf user interface and application software.
		• Assess:
		  • user utility (operational benefits)
		  • usability
		  • performance
		  • reliability
		  • cost

6	Establish (i.e., define and evaluate the feasibility of) the commercial application potential and benefits of the opportunity and detail the technology transfer plan.	A major criteria for government support of and of our enthusiasm for the proposed opportunity is its potential to benefit and be inserted into a wide variety of applications. This objective verifies beneficial impact and establishes a detailed plan to effect it.

2.2 Phase II Objectives

The overall Phase II goal is to produce a fully functional, well-engineered, HPOSS that can be readily commercialized and transferred to our target government and private sector applications. Achieving this overall goal requires accomplishing the following nine major objectives:

Objective 1: To produce a set of generic modular subsystems for performing required HPOSS sensing and communication functions. Much Phase I work addressed the feasibility issues involved in partitioning and integrating base technologies into effective HPOSS functional subsystems. For example, integrating multiple sensors in orthogonal positions into a single subsystem, or integrating a transmitter and power source with sensors into a single subsystem. These subsystems constitute the modular components of the larger body segment units and as such are critical and fundamental to the the use of the product in any application.

Objective 2: To implement computational methods and standards for reliable computation of joint angles from sensor data. The feasibility issues concerning this objective were investigated extensively in Phase I. Our results indicate that standards can be developed to make the needed computations. These standards would fill an important need for any application using HPOSS.

Objective 3: To produce five distinct, ergonomically designed, product packages called Multiple Body Segment Sensing Subsystems (MBS-SS). Each MBS-SS will optimally integrate the sensing and communication subsystems into a single unit assembled with connecting wires and straps to fit a particular body segment (e.g., torso/head, arm, leg). Each MBS-SS will have the capability for real-time sensing and transmitting of the position and orientation of selected body points on a given body segment in three-dimensional space. In Phase I we addressed the feasibility issues associated with the partitioning and integration of subsystems for major body segments and developed feasible design strategies to adopt in Phase II. The MBS-SSs are capable of being used individually or in combination. As such, they relate in different ways to the needs of different application.

Objective 4: To implement computational methods and standards for computing body segment and multiple body segment position and orientation. The feasibility issues concerning this objective were evaluated during Phase I and indicated that computational strategies (e.g., using neural networks) could be developed to overcome the technical complications (e.g., error accumulation). These computational methods and standards are critical to the utility of the HPOSS and therefor are critical to all applications.

Objective 5: To develop a subsystem and computational methods and standards for sensing and communicating body translation. In phase I we addressed the translation issue in a limited manner using a wired solution. This was done to accommodate the need for measuring body translation as part of the total system approach, without having to devote a major part of Phase I effort to it. Strategies for accomplishing this objective were developed while examining feasibility issues. The applicability and need for translation information is dependent on the application, and many applications do not require it.

Objective 6: To develop the multi-receiver, base unit communication subsystem. We include development of the multi-receiver base unit communication subsystem as part of our total system approach to developing the HPOSS. In Phase I commercial units were used successfully to demonstrate the feasibility of the concept. The base unit communication technology is a vital part of the wireless HPOSS concept, and is a major component in the commercial applicability of HPOSS.

Objective 7: To develop the standards for interfacing the HPOSS with application software. We include development of these standards as part of our total system approach to HPOSS. These standards represent the final link between the HPOSS and other virtual reality system technologies

used in the applications. Our Phase I effort did not address this issue, however, its' feasibility is apparent and it' relative success is a matter of the effectiveness and utility of the developed standard to our target applications.

Objective 8: To demonstrate and test the MBS-SSs and associated HPOSS technologies in individually and in combinations in realist application environments, to (1) demonstrate capability, and (2) ensure acceptable and satisfactory performance and usability. Phase I efforts did not directly relate to or address this objective. Assurance that the products meets or exceeds the needs of its intended use is critical to commercial success.

Objective 9: In Phase I we identified several applications for which HPOSS technology would be of benefit. Assessments of HPOSS applicability and benefit were made at a general system capability level rather than with regard to the specific performance requirements needed for each application. In Phase II we will assess these technology transfer opportunities at more detailed levels to gain a full understanding of each applications performance and integration requirements.

Our major Phase II technical objectives, their relationship to Phase I results, and their contribution to the likelihood of successful application are summarized in Table 2 below.

Table 2. Phase II Technical Objectives

Obj.	Description	Related Phase I Results
1	Produce a set of generic modular subsystems for performing required HPOSS sensing and communication functions.	• prototypes developed and tested
2	Refine and implement computational methods and standards for reliable computation of joint angles from sensor data.	• models and standards evaluated
3	Produce (in stages) five distinct, ergonomically designed, product packages, (i.e., MBS-SSs).	• prototypes developed and tested
4	Implement computational methods and standards for computing body segment and multiple body segment position and orientation.	• models and standards evaluated
5	Develop a subsystem and computational methods and standards for sensing and communicating body translation.	• models and standards evaluated
6	Develop the multi-receiver, base unit communication subsystem.	• prototypes developed and tested
7	Develop standards for interfacing the HPOSS with application software.	• none
8	Demonstrate and test the MBS-SSs and associated HPOSS technologies in individually and in combinations in realist application environments.	• none
9	Identify application opportunities and assess specific performance and integration requirements.	• General applicability and benefit of HPOSS assessed for identified applications

2.3 HPOSS Development Overview

Figure 4 puts the Phase I and II technical objectives into perspective with regard to base technologies, research from which the project emanates, Phase I results, and follow-on commercialization plans. The University of Texas at Arlington's (UTA) Human Performance Institute (HPI) has served - and will continue to serve - in the role of the "research institute". HPI has been developing human position/orientation and motion sensing technology for more than a decade primarily for applications in human performance measurement. HPI's groundwork culminated in a research project funded in 1994 by the Texas Advanced Technology Program and which is now being performed at UTA. This currently funded project begins with a vision similar to that portrayed in Figure 1 and focuses on human-computer interface application (i.e., in contrast to performance measurement). This concept is justified by recent developments in sensor technology, wireless local area network technology (and other short-range digital wireless consumer product technology such as cordless phones, wireless stereo speakers, etc.)., and rechargeable battery technology - among others. Recently (to begin Jan 1996), HPI and HPM were jointly awarded a Technology Transfer Grant from the Texas Advanced Technology Program to focus on a single DOF angular position sensor for selected medical applications.

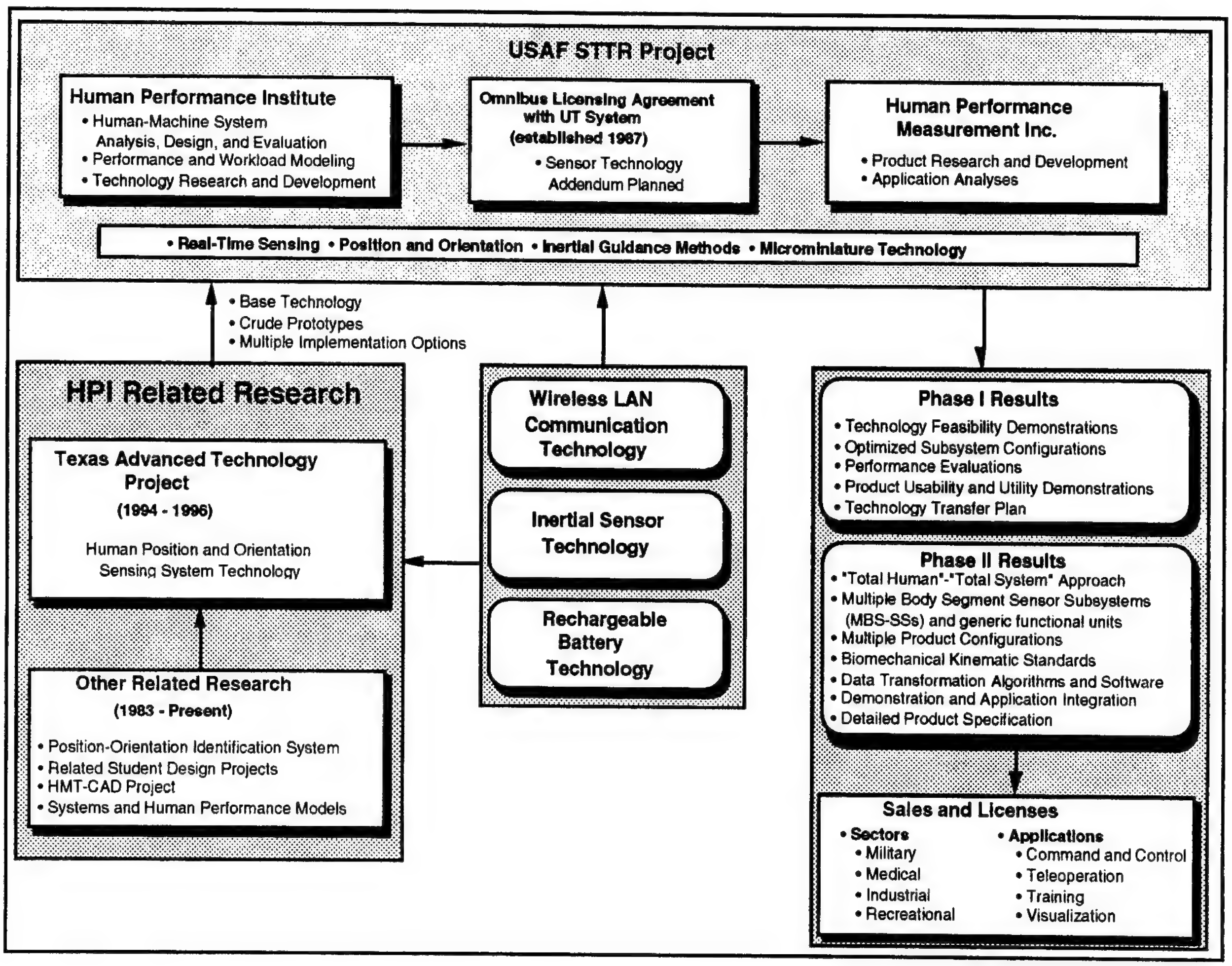


Figure 4. Overview of HPOSS Development and Technology Transfer.

3.0 Progress Summary

This secton summarizes the major accomplishments achieved during Phase I and relates these to Phase I and overall project objectives. More detailed technical information is provided in Section 4.

3.1 Overall Progress and Status of Project

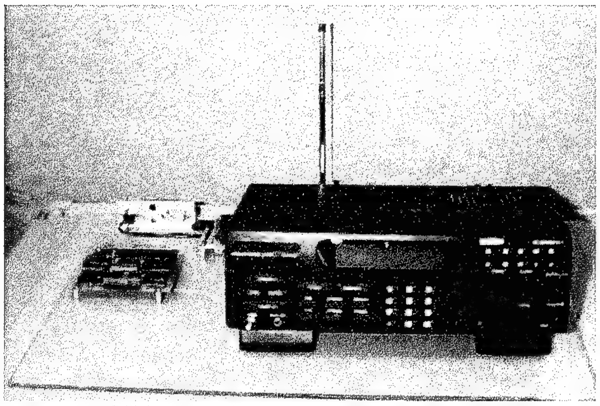
Results obtained from Phase I research and development conclusively demonstrate the feasibility and utility of using microminiature sensing and transmitting technologies to perform reliable, real-time sensing of human body-segment position and orientation in three-dimensional space without the line-of-sight and multi-camera calibration limitiations imposed by optically-based methods. The results demonstrate the commercial potential (1) for transferring the required base technologies into body segment sensing units, (2) for communicating this sensor data, and (3) for computing joint angles from this data. Results were obtained using analysis, modeling, prototyping, and testing methods.

Figure 5 illustrates a MBS-SS prototype for the arm developed and used for Phase I feasibility studies. In addition, we have recently developed and successfully tested a 3 DOF angular orientation Sensor Unit (see Figures 10 and 11) that will replace the magnetic field sensing unit shown in Figure 5. We consider this a "breakthrough" that will signifcantly strengthens what has been the weakest technologic link in our system.

Our Phase I results have:

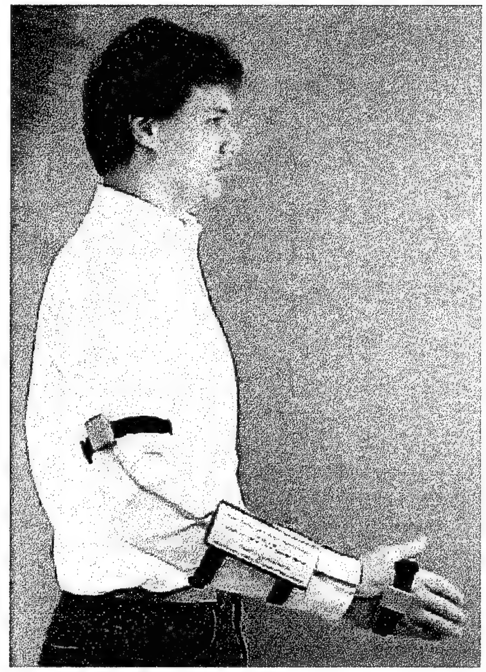
- established the performance and measurment characteristics of the sensing and transmitting technologies,
- verified the human factors practicality of the body segment units,
- validated a mathematical method for interpreting sensor data in terms of position and orientation, verified the application needs of the technology,
- evaluated tradeoffs in various packaging configurations.

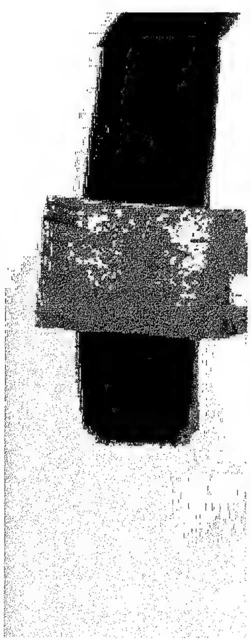
The prototype Phase I systems, the Phase I performance results obtained, the results of related work, and the converging need from potential applications create a great potential for the engineering and application of HPOSS technology. Phase I results demonstrate that available technology can meet the needs of many existing applications. As such the overall goal of Phase I has been successfully accomplished. Our own expectations have been met, if not exceeded.

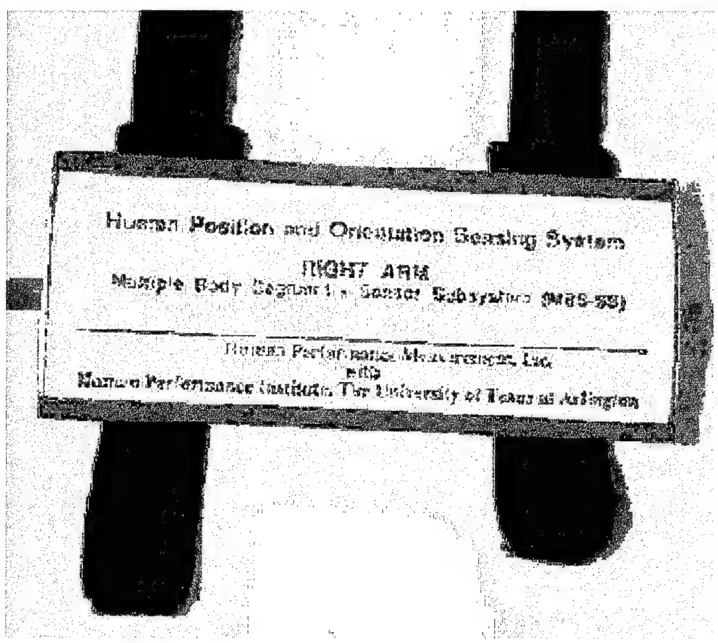


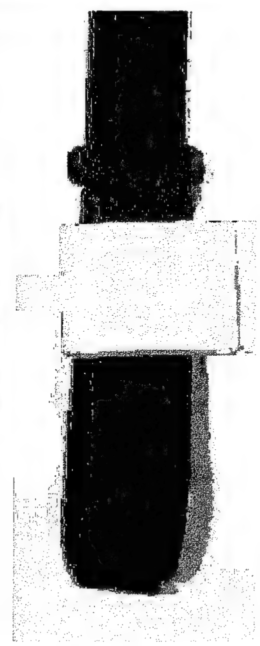
900 MHz Receiver, Microprocessor-based
Decoder, and Host Interface

**Subject with
RIGHT ARM
Mulitple Body Segment
Sensor Subsystem
(MBS-SS)**









UPPER-ARM
3 DOF Sensor Unit
(optional: detachable)

FOREARM Unit: Generically called the Sensor Interface and Control Unit (SICU). Contains microprocessor-based encoder (for 3 arm sensor units), 900 MHz digital FM transmitter, rechargeable battery, power supply, and recharge circuitry.

HAND
3 DOF Sensor Unit
(optional: detachable)

Figure 5. Major components of the prototype Human Position and Orientation Sensing System (HPOSS) developed to date under Phase I funding. Packaging, human factors of donning, biomechanics of human joints, interchangeable sensor units, and wireless communication are part of the "total system" approach investigated.

3.2 Summary of Progress on Specific Phase I Objectives

Assess Technology Options: Options were assessed for each of the the three major base technology areas: sensors, transmitters, and receivers. The most critical technology option impacting the HPOSS involves sensors. A simulation-based approach was developed that models the characteristics of various sensor technologies to aid in this assessment. Both magnetic and inertial sensor options were assessed. The assessment showed that:

- magnetic sensors could be effectively applied in some applications
- inertial sensors provide the better long term solution for most applications
- suitable inertial sensor technology is available now for use in angular orientation sensing systems
- technology for translational position sensing is developing rapidly, but is still not adequate to fill needs in what we have determined to be some of the least demanding applications.

Assess Market Applications: The potential catagories and sectors of applications for HPOSS technology is broad and allows for phased entry and continued development of higher performance systems. See also Sections 1.3 and Section 5.0 of this report.

Develop and Evaluate Candidate Subsystem Designs: Prototypes of various sensor units, wireless communication subsystems, and power subsystemsusing different technology solutions were developed, tested, and demonstrated. In addition various technology alternatives were simulated. The most promising of these are described throughout the report, but particularly in Section 4.0.

Determine Optimal Packaging of Technology Elements: An optimal packaging solution for HPOSS has been defined. Specifically, this packaging strategy involves a set of "Multiple Body Segment Sensing Systems" (MBS-SS), with each using multiple sensor units but only one transmitter. This optimizes many factors over the many different application needs considered (see Figure 5).

Evaluate and Demonstrate Feasibility: Performance data for sensor, transmitter, and receiver technologies has been collected. The overall system concept has been demonstrated using prototypes in a laboratory setting. The data presented in Figures 10 and 11 (in particular) for a 3DOF angular orientation Sensor Unit, along with the detailed descriptions of implementations identifed for other subsystem elements (Section 4.0), demonstrate feasibility for a first commercial product.

Develop a Technology Transfer Plan: A technology transfer plan was developed and is described in detail in Section 5.0.

4.0 Detailed Technical Description of HPOSS Subsystem Designs

During Phase I, we evaluated many design options associated with MBS-SS generic subsystems. Efforts were driven by key developments in base technology areas that we reviewed (see Bibliography). Areas of focus included sensor units for orientation and position (i.e., angular and translational motion, respectively), wireless communication, and rechargeable battery and power source technology. Selected options have been fabricated, succesfully tested, and demonstrated to provide a feasible basis for production of a commercial HPOSS system.

In Figure 6, a prototype Sensor Interface and Control Unit (SICU) is illustrated. This component digitizes up to 12 analog signals, encodes the results for frequency shift keying, and transmits the encoded data in a 900 MHz band reserved for low-power unlicensed use. It is self-contained and battery powered. With the most standard nickel-cadmium batteries, a minimum of four hours of continuous operation is possible. This can be almost tripled with newer battery technology that occupies the same volume (or SICU size can be reduced). The SICU is designed to support data from three different Sensor Units, each of which is itself a 3 DOF angular orientation sensing system. Note that one Sensor Unit is contained *within the SICU* so that the orientation of the body segment on which the SICU is mounted (i.e.; forearm, lower leg, or lumbar spine) can be sensed. For the torso MBS-SS, the SICU's Sensor Unit should also sense 3 DOF position (i.e., 6 DOF total). At present, base technology prohibits incorporation of the intended inertially-based position sensor to accomplish this. We characterize this as a temporary state and have identified a suitable short-term alternative (see Figure 9) that we have defined as part of the overall HPOSS sensing capability for obtaining the position in space of one point on the human.

With regard to Sensor Units, availability of commerical versions of the specific inertial sensors that piqued our interest originally (Barbour, Elwell, and Setterlund, 1992; Elwell, 1991) was delayed until late in Phase I (samples were not avialable in time for evaluation in Phase I). However, some exciting new magnetic field sensing technologies (Brown, 1994) were available and we began to consider this as a potentially viable alternative for short-term and perhaps for the long-term. Figures 7 and 8 illustrate Phase I work using magnetic field sensors (the static magnetic field of the Earth is used as a reference) for angular orientation and inertial sensors for translation, respectively. Furthermore, at the end of Phase I we successfully tested a new intertially-based, angular orientation 3 DOF Sensor Unit (see Figures 10 and 11) that is comparable in size to the magnetic field Sensor Unit (Figure 7) and provided best overall performance (sufficient for a significant subset of commercial applications). In summary, our research has identified not perfect, but viable, alternatives for a first generation implementation of Sensor Units for HPOSS. We have also made a major decision to invest in simulation technology to evaluate the many new accelerometers and other integrated circuit inertial sensors in HPOSS type applications. Such evaluations are near impossible without fabrication and testing, which is slow and costly. The sheer number of new products encouraged this decision. A simulation design tool developed explicitly for this purpose is described and demonstrated below.

The temporary alternative to an inertially-based, *translational* 3 DOF Sensor Unit is illustrated in Figure 9. A crude version of this unique device was developed at the HPI to quantify human performance in tasks that emphasize the motion of a single point on the body such as an end-effector. The two angular DOFs are achieved with a low-mass, damped gimbal-like mechanism. The third DOF, which is linear, is achieved with a mylar tape wound on a constant force spring motor. The tape is prepared with alternating opaque and translucent stripes so that change in position can be sensed by an optical module as it extends or retracts. 3D position measurement of the "end-effector" is achieved via spherical coordinate transformation performed in near real-time (30 Hz rate) by an on-board microcontroller. This subsystem (Single Point Real-Time 3D Digitizer) has emerged as a valuable element of the HPOSS modular component set. It is low-cost, robust (i.e., self-calibrating), and versatile.

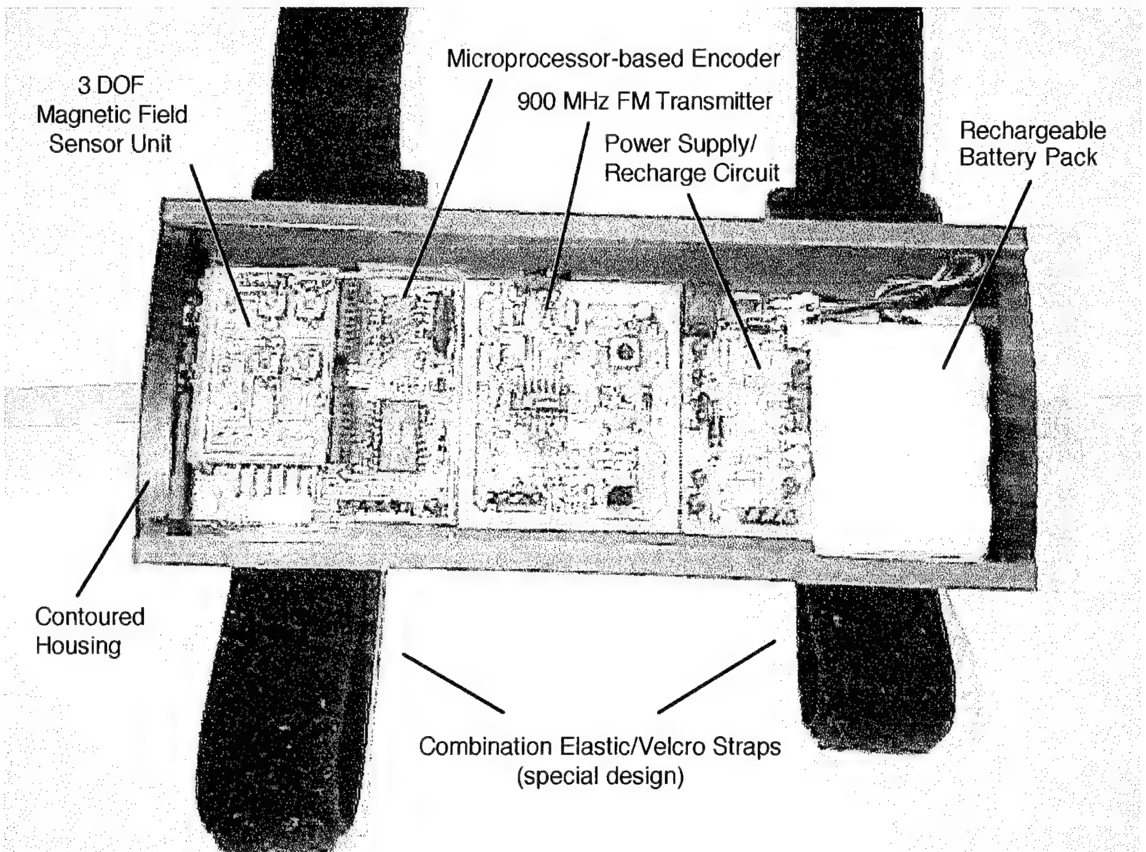


Figure 6. This figure illustrates the internal subsystems associated with the Sensor Interface and Control Unit (SICU) designed and fabricated during the first portion of Phase I. Options were considered for each subsystem; the result illustrated represents what we deem to be an optimal combination. The dimensions of this unit (which would mount on a forearm, lower leg, or the lumbar region of the torso) are approximately 15 cm (6 in). In now ongoing work, we plan to use this design (the magnetic field sensor unit is shown, but we are now substituting an intertial equivalent based on an angular rate sensor). Some size reduction will be achieved (approx. 20% in all dimensions) when fewer independent printed circuit boards are used and a pre-production housing is employed.

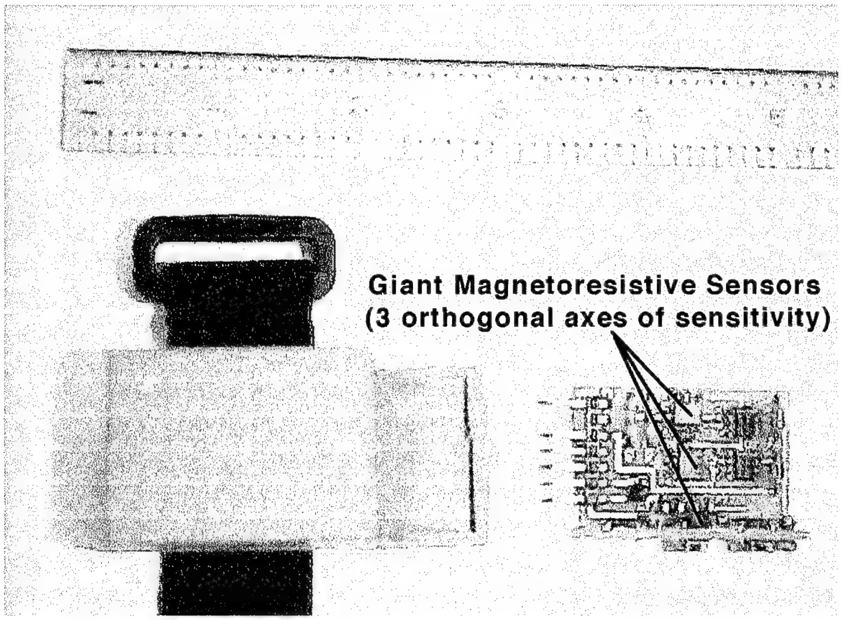


Figure 7. Prototype 3 DOF magnetic field sensor unit developed and tested during Phase I. Good results were obtained using new, low-cost, high sensitivity "giant magnetoresistive" (GMR) technology making the case compelling to seriously pursue using the earth's magnetic field as a reference and a magnetic field sensor unit as a feasible option for HPOSS.

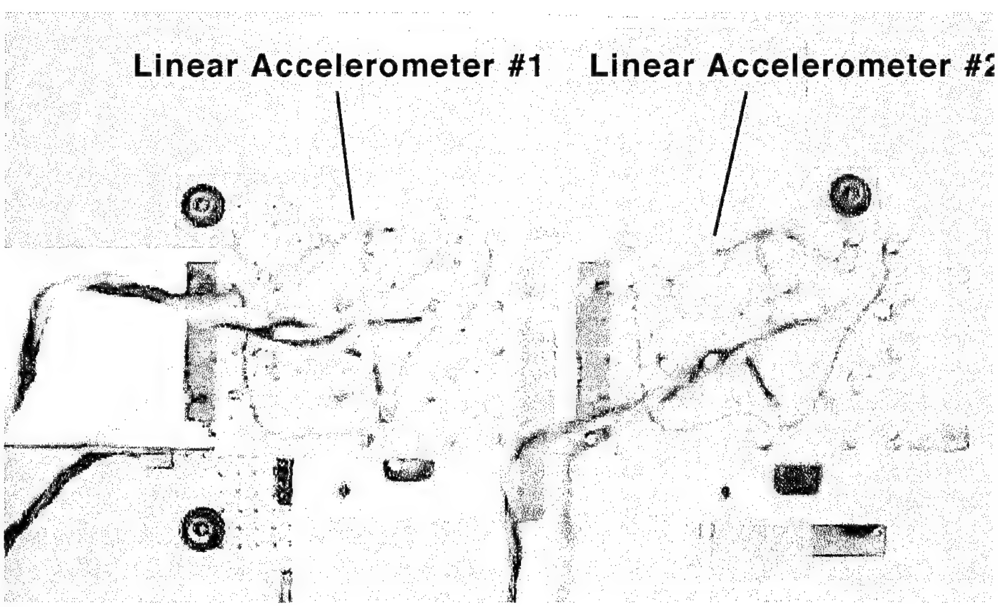


Figure 8. Prototype of a single degree of freedom orientation sensor formed using two translational motion accelerometers with excellent performance characteristics and low cost (approx. $20 each). These sensors just recently became available from Analog Devices (May 1995); we anticipate other units (e.g., multi-axis devices) from this source in the near future. The unit shown was not optimized for size; rather the goal was to produce a unit for experimental testing and to validate the Inertial Measurement Simulator (see text).

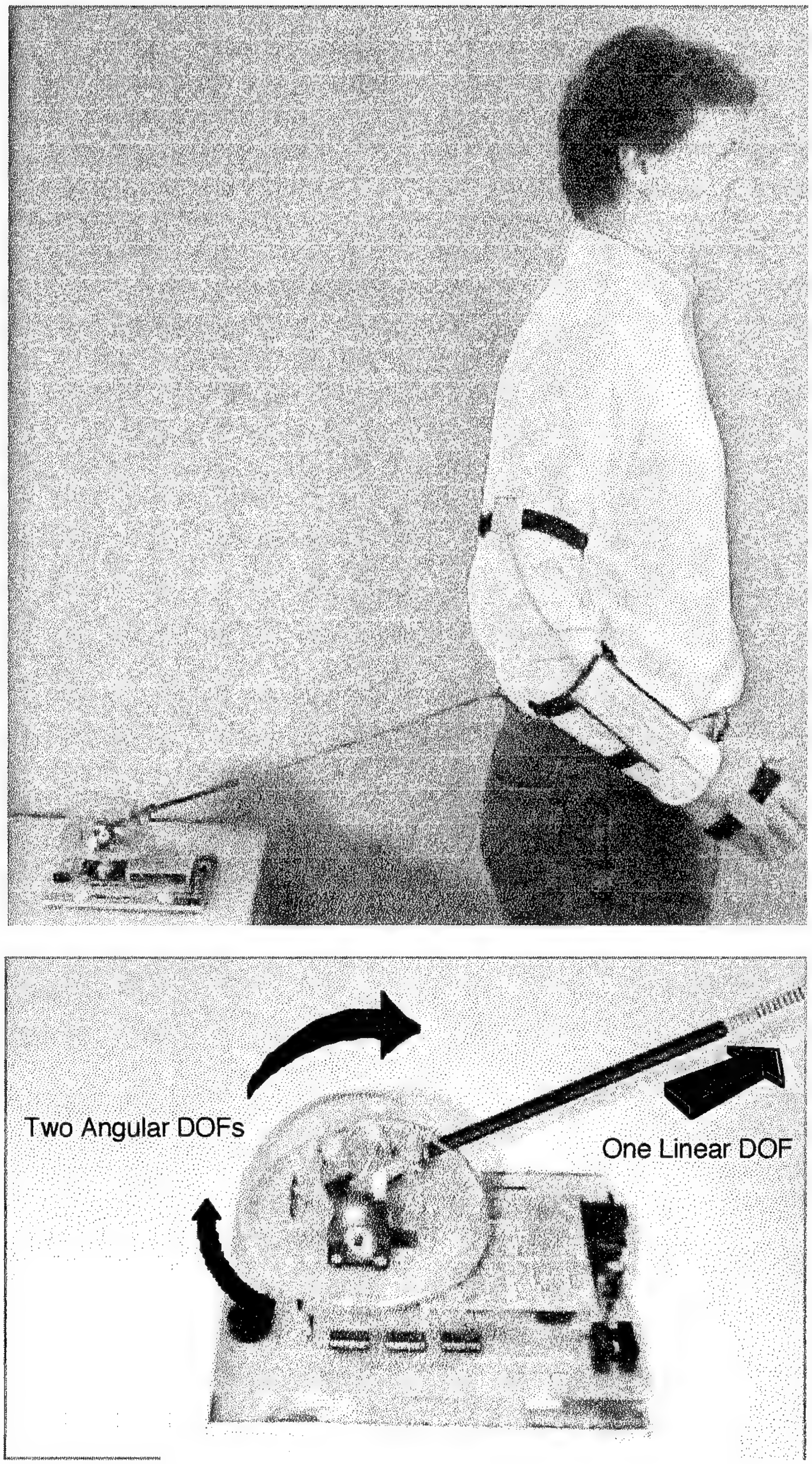


Figure 9. This unique "Single Point, Real-Time 3 Dimensional Digitizer" (SPRT-3D) was developed as a temporary substitute for an inertially-based *translational* motion tracking instrument. It can track the position of a single specified point with good range and fidelity. This suffices for "total human" kinematic specification if knowledge of body segment lengths and segment angular orientation is also available.

4.1 Sensor Units

Of the several critical base technologies upon which HPOSS depends, sensor technology offers the most design options and greatest tradeoff challenges at present. We have pursued two broad categories: (1) micromachined inertial sensors, and (2) magnetic field sensors (specifically with the intent of using only the earth's magnetic field; i.e., no artificially generated fields are used). Within these broad categories, we have been investigated alternatives available in the form of commercial components (modules and integrated circuits) that could be either used as is (none identified) or used *within a Sensor Unit system of our own design* (some identified). Each of the many products evaluated has its own advantages and disadvantages, making it difficult for a single, clear choice to emerge to fill all requirements for HPOSS. At least one feasible option has been identified for orientation and position sensing. In addition, we consider prospects for the emergence of other integrated circuit accelerometers and rate sensors to be excellent.

One important simplifying observation that has been incorporated into the top-level of HPOSS design is that many applications can be served simply with orientation information and that sensing position of only a single point on the body will suffice for extension to another wide range of applications. This resulted in an emphasis on orientation sensing, which we intend to continue to pursue. With inertial methods, it is necessary to compensate the outputs of translational motion sensors (e.g., accelerometers) for angular motion, whereas the converse is not true. Thus, a good orientation sensor is a necessary prerequisite for any translational motion position sensor. In Phase II, we will continue this prioritization.

Based on these results, we have concluded that two paths should be pursued for both orientation sensor units (inertial and magnetic field) and position sensor units (inertial and a electromechanical device called the Single Point Real-Time 3 Dimensional Digitizer (SPRT-3D). Phase I results are summarized for each of these four thrusts below.

4.1.1 Inertial Orientation Sensors

Recent contacts with individuals at Rockwell International (the technology transfer firm for microminiature intertial sensor technology developed at Draper Laboratories that strongly attracted the interest of HPM's technology transfer source at the University of Texas at Arlington) tempered our hopes with regard to the short-term availability of suitable integrated circuits for low-cost, high-performance inertially based systems. However, the late-breaking discovery of an interesting angular rate sensor IC (Murata Corporation) has rejuvinated our original expectations for a first generation system.

Rockwell's first prototypes will not be available until January 1996 and these will only be single degree-of-freedom units. It was initially reported that Rockwell would produce a commercial version of the six degree of freedom integrated circuit prototyped by Draper (Barbour, Elwell, and Setterlund, 1992). This is still expected to occur, but not in the time frame originally anticipated. AMP, Inc. has also introducted an interesting inertial sensor IC (piezoelectric) with two translational and one rotational degrees of freedom. Both Rockwell and AMP have targeted automotive applications. AMP sensors do not have d.c. response and in fact have a lower cutoff frequency of 13 Hz. While this may serve well in automotive applications, it is too high for sensing the human motions of interest. There still might be some hope for utilizing this device with special signal conditioning electronics. In very recent discussions with AMP personnel (Mr. Chris Henry), it was learned that AMP had an "engineering version" of a 3DOF translational sensor with a response down to about 0.3Hz. Furthermore, a version of this device with on-chip, programmable signal conditioning was expected by late 1996.

We have begun to develop a strategy for educating the leading manufacturers of such devices about the requirements - and the market - for human sensing applications. Analog Devices has just

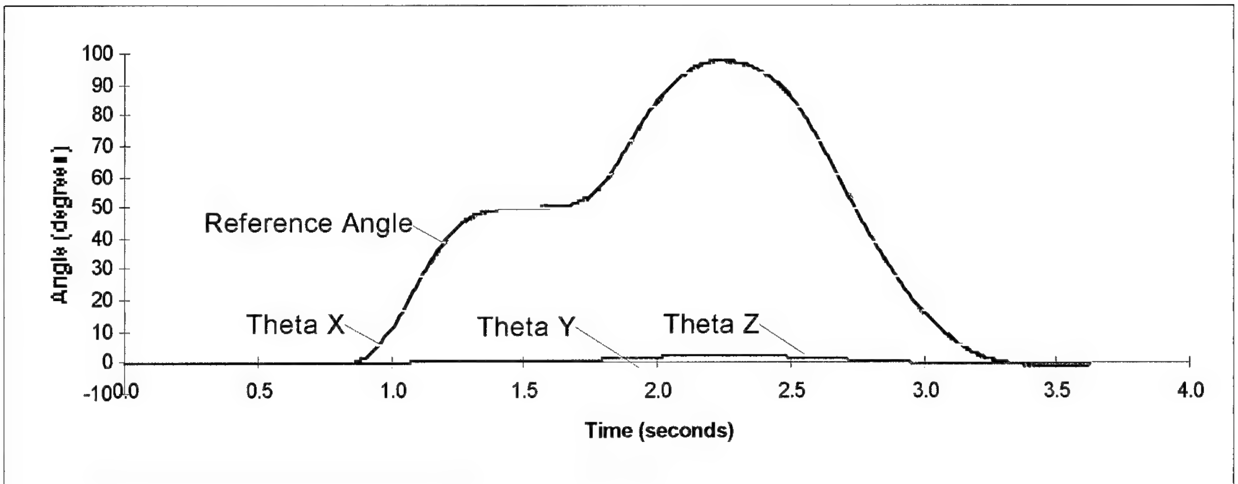
introduced (May 1995) a higher resolution version of their integrated circuit, micromachined accelerometer (the ADXL05 with a ±5 g range, compared to the ±50 g range of its predecessor) and seem very serious about continuing the expansion of this product line. Other products (e.g., vibrational gyroscopes) are module level and are currently too large for the defined HPOSS needs.

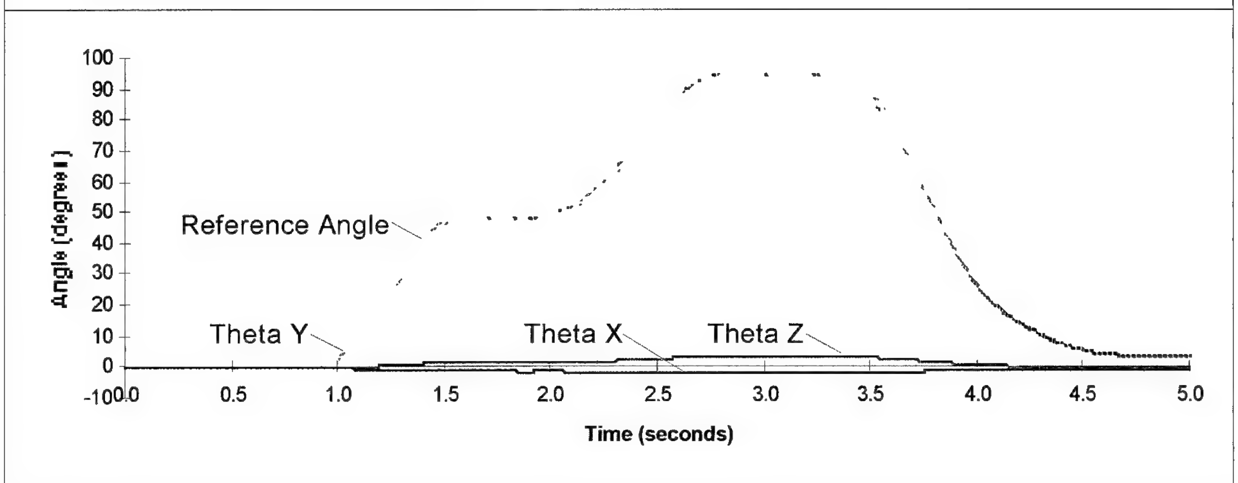
Murata has advertised an angular rate sensing module since at least 1995. The unit was rather large and expensive, but exhibited good performance with regard to accuracy and rate range. During a routine exploration of price and availability of this module for potential use as a lab reference, it was serendipitously discovered that Murate also produced a version of this sensor in a much smaller package for use in video camera image stabilization systems. Special arrangements were made with Murata's product line manager to purchase sample units. Preliminary tests of a single unit were very promising; we proceeded to develop a 3DOF angular orientation Sensing Unit with these devices. Signal conditioning hardware (one stage amplifier) and microprocessor-based software (for integration and other non-linear error reduction schemes) were developed to enable further testing. The 3DOF Sensor Unit package resulting was a small cylinder (approx. 2.5 cm diameter x 1 cm long).

Data representative of our most recent tests is illustrated in Figures 10 and 11. For data in Figure 10, the package was mounted on special test fixture that allowed the orientation to be manually changed while both reference data and the three conditioned Sensor Unit outputs were digitized. The Sensor Unit was mounted in three different orientations, chosen to excite each of the three axes of sensitivity. Over test times up to 10 seconds, errors of less than 1 degree were readily obtainable.

Figure 11 illustrates the 3DOF Sensor Unit mounted as it would be as part of a MBS-SS and the typical data obtained.

In summary, this approach is reasonably low-cost and provides good accuracy in orientation sensing. Due to our strategy which relies primarily on orientation (versus position), we are confident that the Murata sensor level device could fill the basic sensor element niche in a first generation HPOSS product.





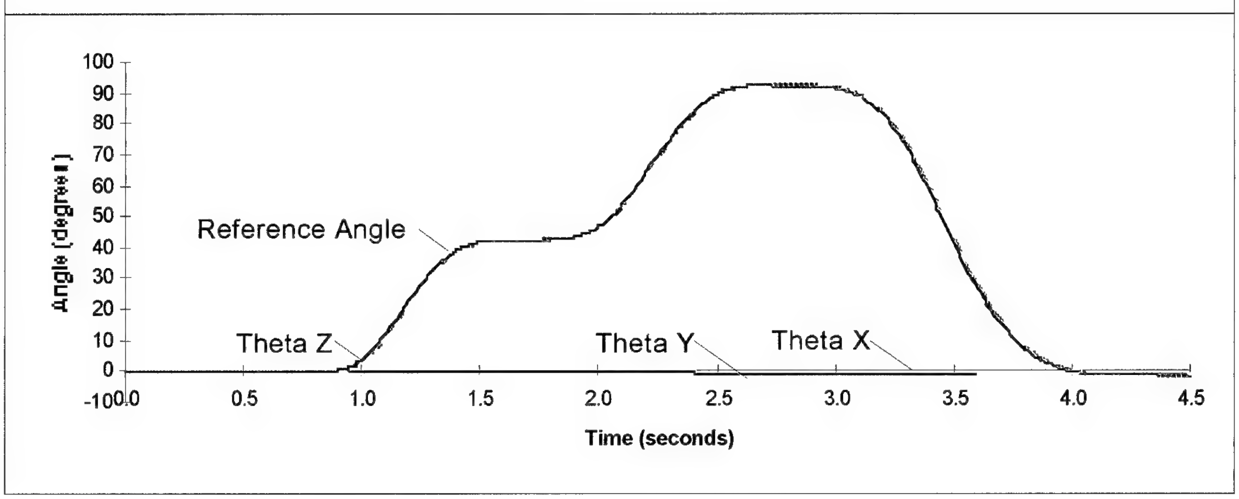
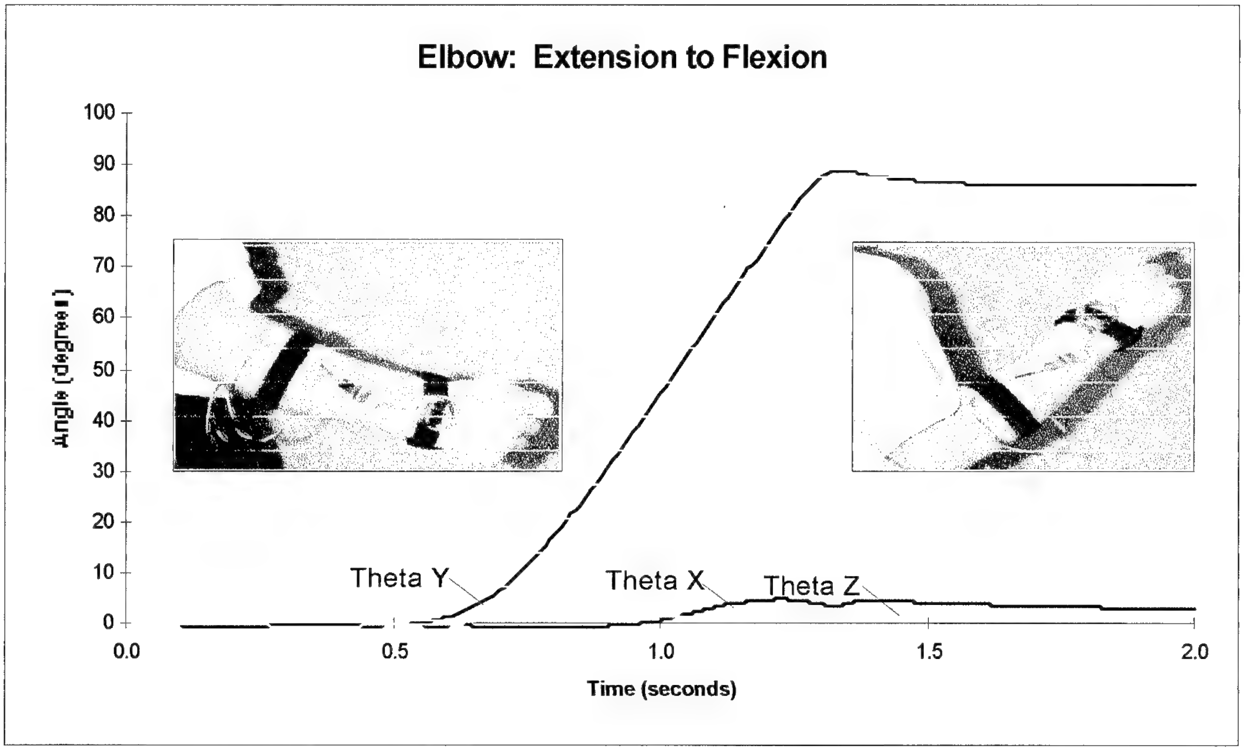


Figure 10. Data from three experiments to evaluate intertially-based, 3 DOF angular orientation Sensor Unit incorporating recently available angular velocity sensors (see Figure 11). In each experiment, motion of Sensor Unit is restricted to one of the three sensitive axes, while all three Sensor Unit outputs (i.e., Theta X, Y, and Z) and a calibrated reference sensor output are recorded. The inertially-based sensor output is virtually indistinguishable from the reference output. Cross-talk is minimal.



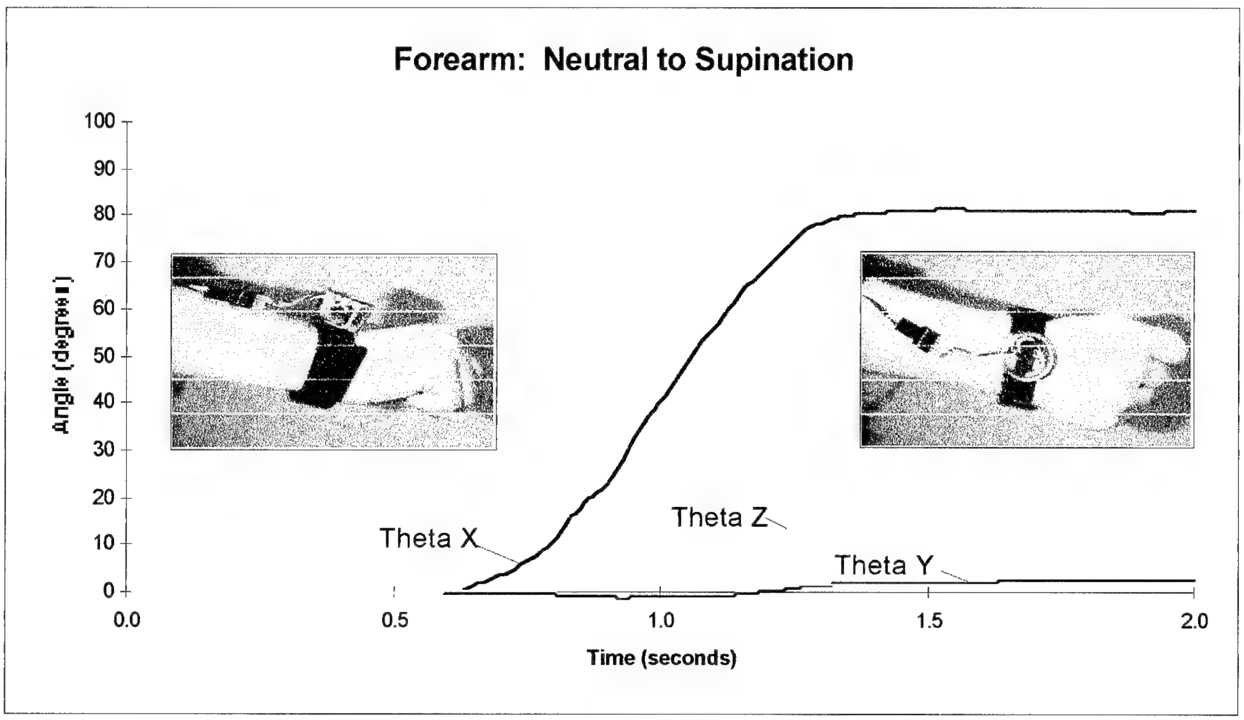


Figure 11. Evaluation of the inertially-based 3DOF angular orientation Sensory Unit (pink box) now serving as the Sensor Unit that would be contained within an SICU and which would monitor distal forearm orientation. The upper plot illustrates the output when the forearm is rotated about the elbow (from extended to flexed position). The lower plot illustrates an extended arm with a rotation from a pronated to neutral orientation.

4.1.2 Simulation of Inertially-Based Position and Orientation Sensing Systems

The capability to translate and interpret the raw Sensor Unit data into meaningful information about body segment angles is critical to the utility of the orientation sensor system. For inertially-based sensors in particular, a given sensor unit would typically be composed of several "more basic" sensors (e.g. gyros or accelerometers) whose outputs are combined in either a one-to-one or many-to-one fashion to produce one of the SU's outputs. Since there are many module and integrated circuit-level products now appearing on the market, and because it is difficult to infer performance of a human orientation sensor from a direct observation of the performance specifications of one or more sensors combined to form a given HPOSS "Sensor Unit", in Phase I we developed a performance modeling and simulation tool (the Intertial Measurement Simulation software, or IMS) as our primary primary basis for continuing pursuit of the use of inertial sensors in HPOSS. The prototype tool now being developed allows: (1) specification of system configuration for a given SU design (i.e., the types of sensors, such as rate gyros or accelerometers), (2) characterization of each basic sensor in a given configuration in terms of its performance specifications (available from sensor manufacturers), and (3) specfication of trajectories and sequences of trajectories for a hypothetical, body-mounted SU package (which are based on our "human-factored" considerations), and (4) estimation of overall performance specifications (e.g. elbow flexor-extensor angle accuracy) for the simulated SU in the given simulated application.

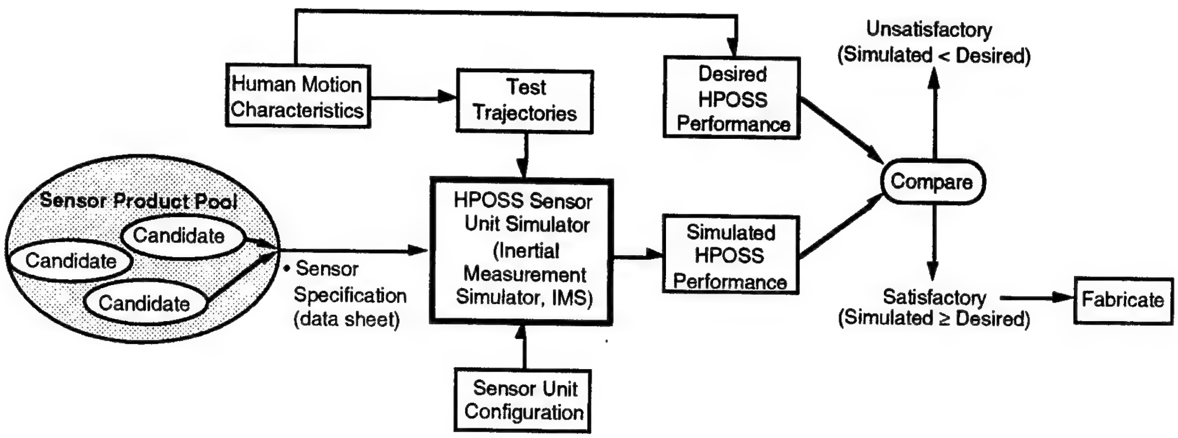


Figure 12. Simulation of HPOSS Sensor Unit designs will be used to screen commerically available inertial sensor candidates (alone and in architectures that require the combination of two or more sensor). Predicted performance and established performance criteria (e.g., minimal acceptable accuracy) will be used to decide which candidates will be selected for Sensor Unit fabrication.

The algorithms developed to support this simulation are fundamentally the same as those required on the receiver/decoder end for properly interpretting raw sensor outputs in an actual physical implementation. Thus, we move forward with development of the software component of an intertially based system, while using simulation as an alternative (or more accurately, a preliminary step) to prototype fabrication of hardware. In parallel, our university colleagues have initiated a database to track intertial sensor products and their performance specifications. We plan to use this, along with experimentally derived data sets that characterize typical and extremes of human motion to drive the simulation model. When a given configuration and product combination is obtained that yields satisfactory results in the simulated evnironments, we will proceed to fabricate a prototype.

Inertial Measurement Simulation Example: Use of the IMS software to model a 1 DOF angular motion sensor (that was also fabricated using the recently available Analog Devices ADXL05 sensors and then tested - see below) is briefly described. The configuration is illustrated in Figure 12 (see Figure 8 for a photo of the physical test unit).

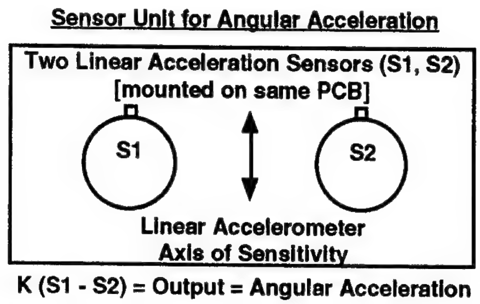


Figure 13. A sensor unit architecture that combines the outputs from two linear motion accelerometers to achieve only angular motion sensitivity for one degree of freedom. This architecture was used to demonstrate and test the Inertial Measurement Simulation software. A physical version has also been fabricated and tested.

This Sensor Unit consisted of only two accelerometers with a sensitivity of 1 V/G, a signal conditioning unit, and an A/D unit. Specification of the physical configuration of the Sensor Unit is illustrated in Figure 13.

As illustrated, the two accelerometers are placed on the sensor unit's Y-axis with the same relative orientation, but at a position 25 mm to the left and right of the origin. In this configuration, positive angular accelerations about the Z-axis are recorded as a positive value by the accelerometer positioned to the left of the origin and as a negative value equal in magnitude by the accelerometer positioned to the right of the origin.

Signals from each of these accelerometers are then "signal conditioned" to provide a difference signal using a simulated differential amplifier. The equation representing the output at this subsystem is:

$$\text{Voltage}_{accel} = \text{Gain x } (S1_{out} - S2_{out})/2$$

Any mathematical formulation can be readily specified to the IMS. Quantization is performed mathematically on the signal conditioned data given a user specified number of A/D bits.

Options exist for special signal mixing (none used in this example) and specification of other sensor parameters (e.g., accuracy, etc.). Standard physics equations are used to determine response to input data that drives the simulation. No gravity compensation was employed in this run.

The input data was orthogonal to the gravity vector. It represents 3 DOF motion (2 translational, 1 angular; the remaining three DOFs were constant) of the distal portion of the upper arm in space that results from several horizontal abduction-adduction cycles of the right shoulder joint over a 10 second period. Position data was captured at a 20 Hz sampling rate using a special mechanical gimbal sensor system. IMS software allows examinination of input data, as illustrated in Figure 15 for the present example..

The translational velocity and acceleration along the X & Y-axes were calculated from the corresponding positional data. Likewise, the angular velocity and acceleration were also calculated.

Using the basic system design and input data described above, several simulation trials were executed to investigate differences in the Sensor Unit's measurement error for changes in A/D bits (quantization levels) and for small physical angular offsets between the two accelerometers.

The first simulation was performed using ideal conditions; results are shown in Figure 16. The second and third runs used 10 and 12 bit A/D converters, respectively, to quantize data. Results are shown in Figure 17. For the fourth trial, a small 2° angular offset about two axes between the two accelerometers was defined; results are shown in Figure 18.

Simulation results show that this 1-DOF inertial measurement design performs very well at measuring only angular motion when subjected to both translation and angular motion. From the results, it can be seen that the size of the quantization level has a large effect in the output orientation error. Also, the need for a good calibration method is required to minimize the errors due to alignment errors between individual sensors in a sensor unit (this error can be removed during processing since it is fixed).

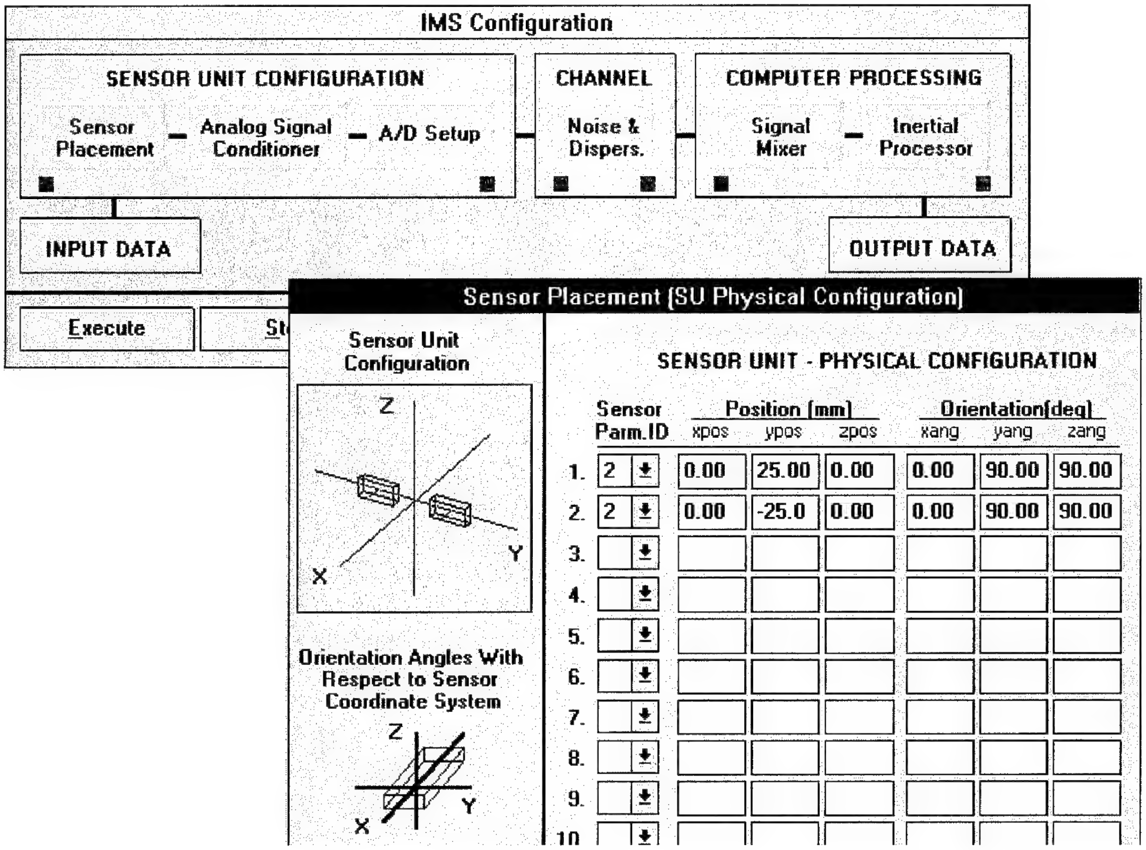


Figure 14. IMS software screen snapshot illustrating means for setting variables that dictate the physical configuration of the simulated Sensor Unit.

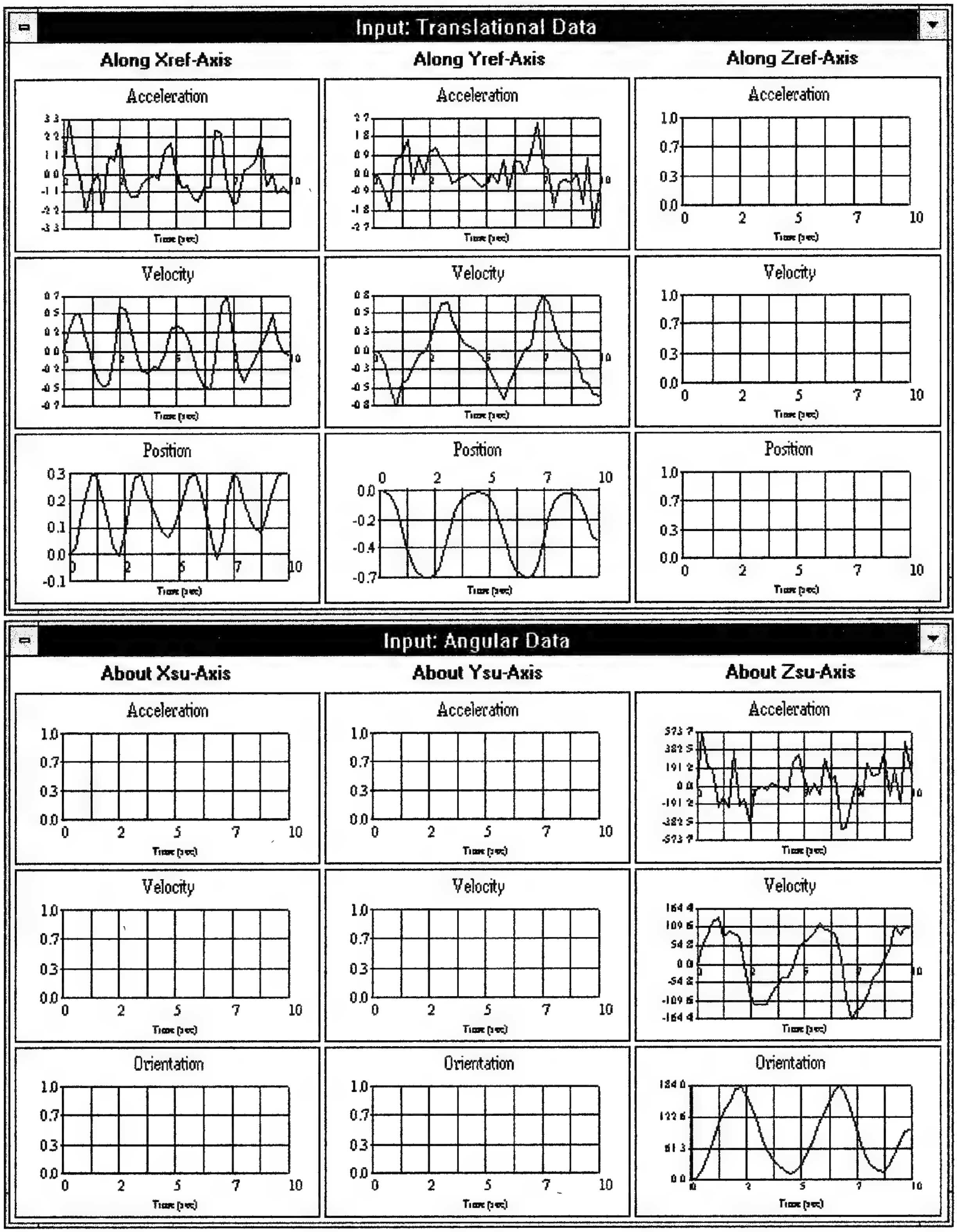


Figure 15. Three dimensional translational motion time series data, representing the trajectory of the simulated Sensor Unit's geometric center, drives simulation runs.

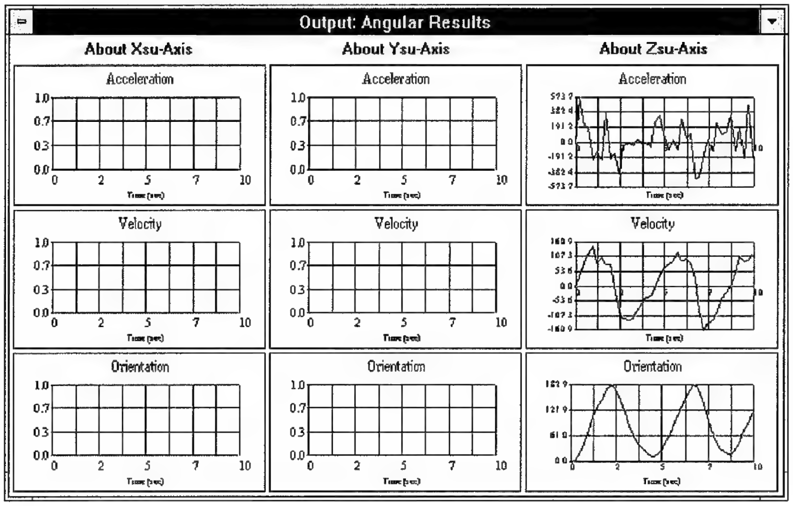


Figure 16. Output orientation, angular velocity & acceleration (about Z-axis) with ideal settings for all subsystem parameters.

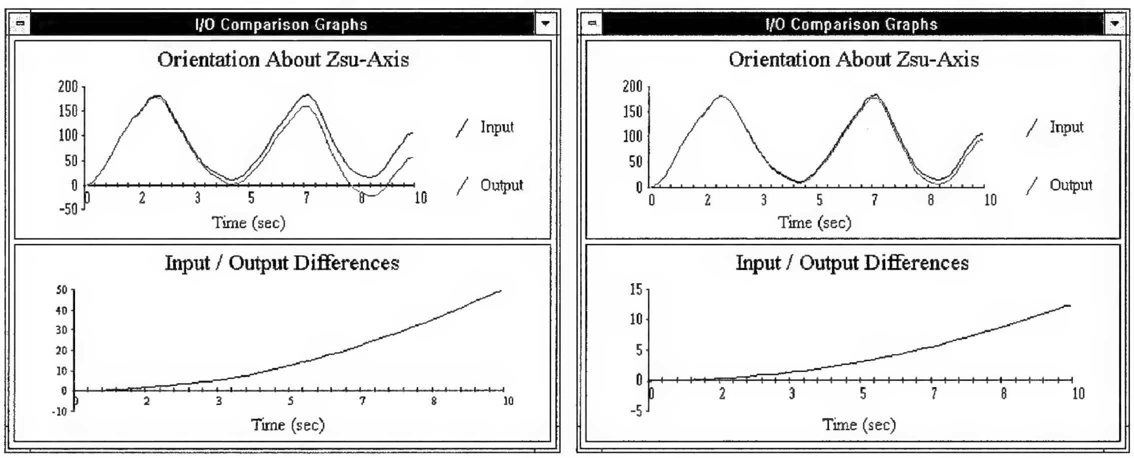


Figure 17. Simulation indicating orientation error as about the Z-Axis as a function of time when using a 10 Bit A/D (left) and 12 bit A/D (right).

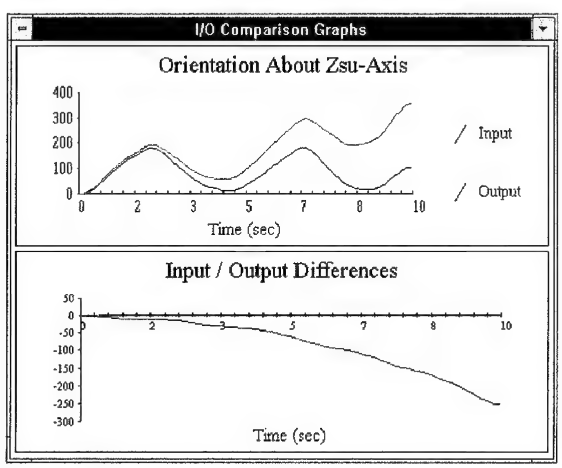


Figure 18. Z-axis orientation error with 2° accelerometer alignment error.

A Fabricated 1 DOF Orientation Sensor Unit: The configuration simulated above was fabricated as noted using Analog Device sensors, op-amp signal conditioning, 12 bit digitization, and digital integration with a microprocessor. Results of a pendulum test are shown in Figure 19.

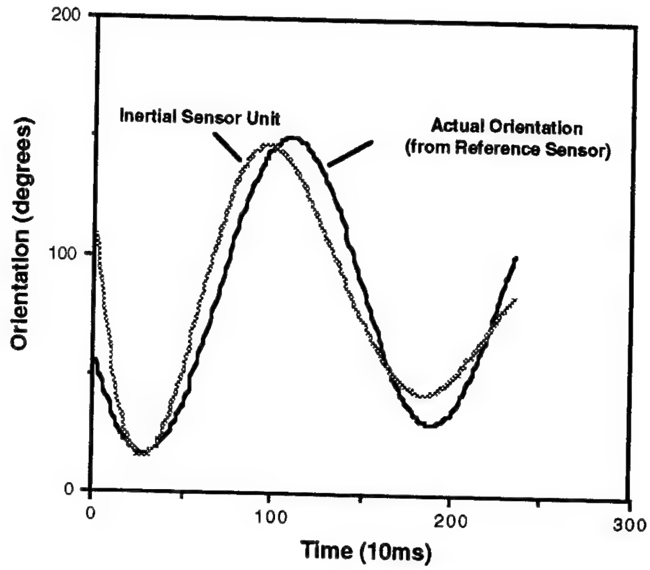


Figure 19. Performance of an initial 1 DOF orientation Sensor Unit fabricated with two Analog Devices ADXL05 linear motion accelerometers. Compared with our latest orientation Sensor Unit (Figures 10 and 11), based on a single rate sensor IC, this unit based on two translational accelerometer ICs is less accurate. However, it illustrates the variety of configurations possible for Sensor Unit design.

4.1.3 Magnetic Field Orientation Sensors with Earth's Field as a Reference

In addition to inertial techniques, recent new developments in magnetic field sensing (Giant MagnetoResistive, or GMR, sensors, e.g. Brown; 1994) have compelled us to give serious consideration to using the earth's magnetic field for sensing the orientation of human body segments. Although our position remains that the inertially-based sensor systems are ultimately the best solution, as indicated above the base technology is not yet available in suitable forms and with performance specifications that would be sufficient to neglect other alternatives. Compared to inertial sensors, our Phase I work with the GMR-based sensors indicates that they are: (1) less expensive, (2) currently smaller, lower weight, and require less power, (3) solve quite a few of the human factors problems, (4) use the earth's d.c. field, which allows filtering of most environmental interference sources, and (5) neglecting interference from large ferromagnetic objects, they theoretically provide better long-term accuracy than inertial sensors because drift (which is currently a major limiting performance factor of inertial sensors) is not as great of an issue because the sensor's output does not have to be mathematically integrated.

Initial Magnetic Field Sensor Unit test results indicate: (1) an unexpected small but significant drift of unknown origin, (2) higher than expected failures of the basic GMR sensor integrated circuits, (3) good basic sensing performance with regard to accurately sensing the magnetic field strength of the earth when the unit is used in different environments and in different positions. The GMR IC manufacturer has been contacted with regard to items (1) and (2); we believe these will be remedied (the ICs we used were from the first production run). Results were encouraging enough for our stable prototype units to be used in a university-based experiment aimed at an investigation of upper extremity speed-accuracy tradeoffs. These were limited, however, to motion in a single plane since software that combines all three orthogonal GMR sensor outputs to

produce the required three orientation angles has not been settled on. Theoretically, ambiguities in orientation are possible with three orthogonal magnetic field sensors housed in a single unit whose orientation changes with respect to the earth's magnetic field vector. While this prohibits development of a closed form mathematical equation to convert field strengths to body segment angles, we have characterized them to be "unlikely" events in most human motions. A neural net model which can resolve ambiguities by utilizing the previously calculated gimble angles has been evaluated with experimental data and encouraging results were obtained (Figure 20). Additionally, a test using actual time-series data from a mechanical 3DOF reference sensor and a magnetic field-base SU has been performed for which no ambiguities were found; i.e. a unique mapping of MFSU output to gimbal angle representation would be possible. Thus, while not our final choice, a simple look-up table approach to achieve this mapping appears feasible.

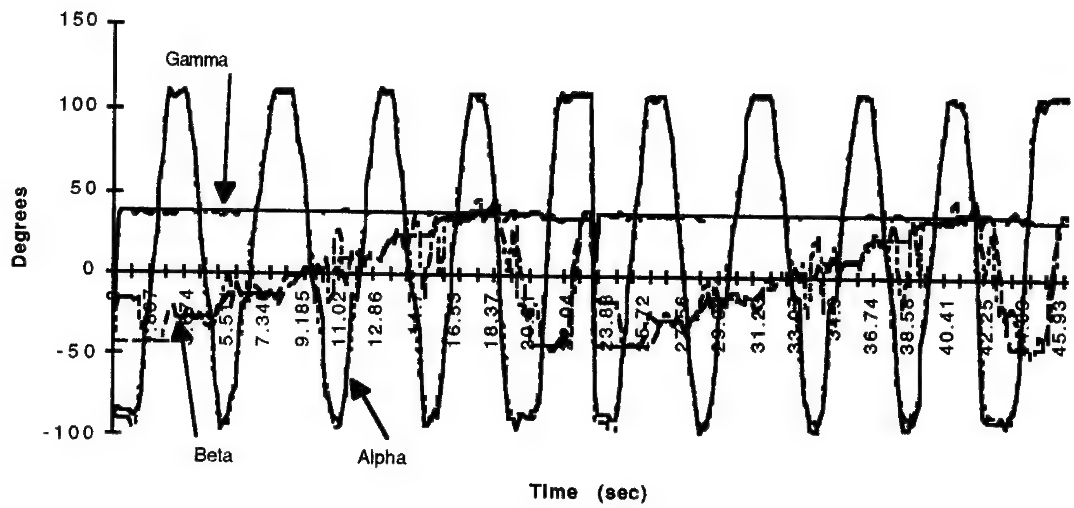


Figure 20. Results of initial experiment aimed at using a neural network to map magnetic field sensor outputs to an Euler angle representation. Reference and predicted time series values are shown for the three angles of interest, appearing as three groups (labeled Alpha, Beta, and Gamma) of quite closely matched pairs (e.g., reference and predicted) of time series, indicating reasonably successful decoding of magnetic field sensor outputs by the neural network.

We have maintained close contact with our magnetic field sensor supplier. The following highlights a telecon with Mr. Russ Beech, Test Engineer at Nonvolatile Electronics, Inc. on 14 July 1995 regarding their current and proposed line of device-level GMR magnetic field sensors:

- There have been NO changes to the model NVS5B50 that we have been using and none are currently planned.
- A low field (NVS5B15, 15 Gauss) sensor, that is otherwis identical to the NVS5B50, is currently in development and samples should be available in six weeks. Production parts should be available by mid-September 1995. This should substantially reduce effective noise and improve performance noticeably over what we have achieved to date.
- NVE has recognized a need for sensors for "compass-type" use (i.e., sensing the earth's magnetic field). However, a production date is unknown.
- A GMR sensor with an integrated amplifier is in development but compatibility problems with the GMR and IC materials have pushed delivery into 1996. This will ultimately allow reduction in Sensor Unit size over what we have been able to achieve currently (e.g., see Figure 7).
- NVE has demostrated the ability to manufacture sensors with uG noise levels although not in production quantities as of yet.

In addition to these forthcoming NVE developments, Honeywell has recently announced integrated multi-dimensional sensors intended for sensing the Earth's magnetic field specifically. Preliminary data indicates that these are small (slightly smaller than the 3 DOF units we fabricated) and low cost. We are in the process of obtaining samples at present.

4.1.4 Inertial Position Sensors

Much of the discussion contained in Section 3.2.1.1 (for Inertial Orientation Sensors) applies equally well to measurement of translational motion (i.e., change in position). Our plan is thus similar. We plan to fabricate a 3 DOF inertially based postion sensor and evaluate its performance. The IMS sofware will be used to first simulate the architecture. Size is of less importance since only the 3DOF position of the torso lumbar segment is required; the size of the torso relative for the arm or leg allows for modest package size increases (i.e., for the torso MBS-SS) over our prototype (e.g. Figure 6). We fully anticipate that a working model can be obtained. However, the level of fidelity that would be possible remains an issue that depends substantially the pace of base technology developments. As of this time, the Analog Devices ADXL05 appears to be the optimal choice and our first prototype will be based on these ICs.

4.1.5 Single-Point, Real-Time 3D Digitizer

This component does what its name implies; i.e. measures the x,y,z coordinates of a single point over a large volume at within approximately 1 mm. accuracy. It was incorporated as a temporary but novel substitute for an inertial means of measuring the position of a human in a workspace or one point on the human (e.g, the hand) in space. The device (Figures 9 and 21) consists of a mechanism allowing computation of the x, y, z coordinates of the tip of a vector using a polar coordinate system, three optical encoder position sensors (two angular, one linear), and a micrprocessor that commununicates with a host PC. The mechanism consists of a low-mass, carefully balanced gimbal on which a spring motor is mounted. A special mylar tape with alternating translucent and opaque strips is wound around the hub of the spring motor. It passes through a short, stiff tube afixed to the inner ring of the gimbal. When the end of this tape is pulled (< 2 kgf is required), the length of tape can be measured with a linear optical encoder through which the mylar tape passes. The stiff tube causes the gimbal to rotate to balance forces; i.e. track the "pivoting" radius vector (within limits due to gimbal singularities).

One prototype of a new generation design has been constructed that performed quite well. Coordinates can be digitized at rates up to 30 Hz to within at least 2-3 mm. Refering to Figure 21, angle "α" can vary over a full 360 degrees, the range for "B" is just less than 90 degrees (to avoid gimbal singularities), and "r" ranges from 0-2.5 m. Dynamics are also quite good; when connected to a point on the torso near a subject's center of gravity (which is high mass and does not change position very rapidly), no observable oscillations were found.

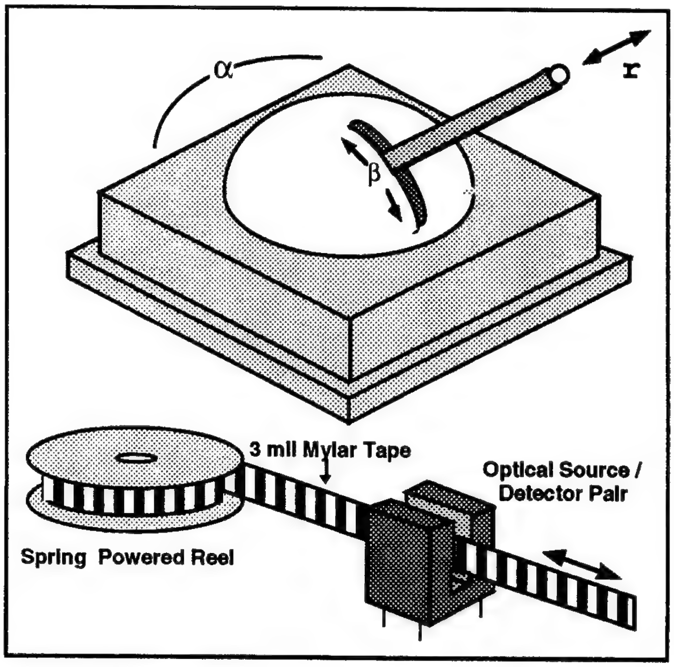


Figure 21. Novel SPRT-3D mechanism and examples of its application in measuring human structure and performance (see Figure 10 also).

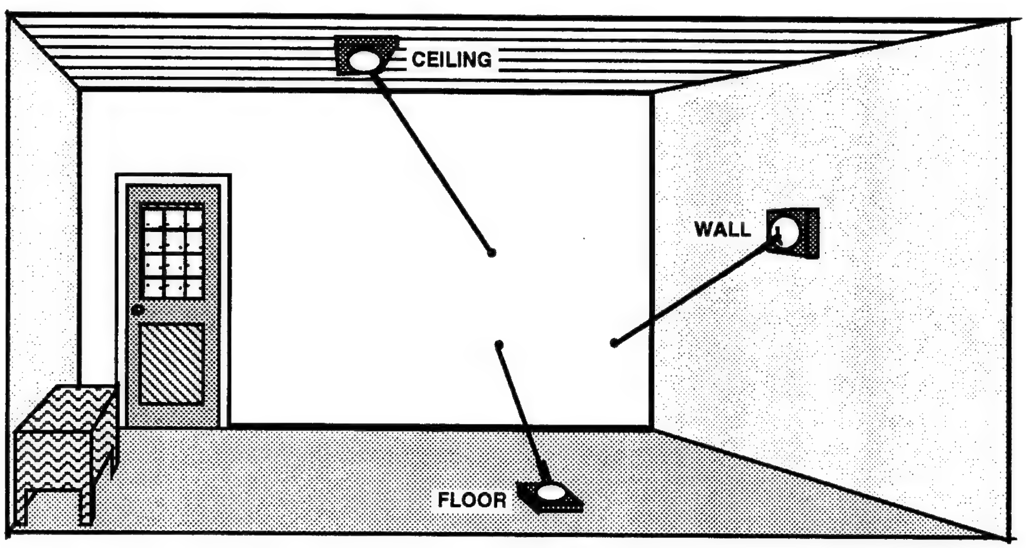


Figure 22. The Single-Point Real-Time 3D Digitizer (SPRT-3D) is readily adapted to different environmental constraints.

4.2 Sensor Interface and Control Unit (SICU)

Two categories of issues associated with the SICU were addressed in Phase I: (1) electronic, and (2) human factors. Very favorable results have been obtained in both cases, with our final results very much like our original vision prior to the commencement of Phase I (i.e., compare Figures 1 and 5).

While the basic systems-level architecture remained quite stable, numerous options were investigated for realization of individual functional elements (the SICU was the focus topic of two senior electrical engineering design courses). In this regard, final design decisions are summarized in Figure 23. The prototype SICU weighs 164 g (5.78 oz.) including batteries. In Phase II, we propose to freeze the SICU design, concentrating primarily on packaging improvement and size reduction. In the subsections that follow, some key issues associated with each system are highlighted. For all, future work is primarily "fine-tuning" and replication as necessary to meet quantity requirements. At the same time, our design permits the option to upgrade selected components as new options become available that are offer significant improvements.

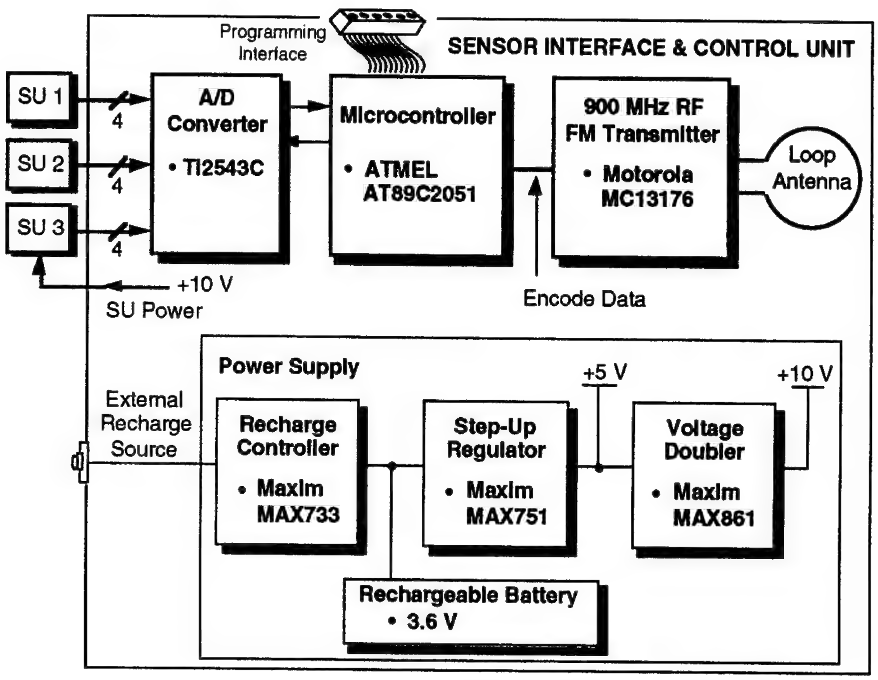


Figure 23. SICU block diagram with key decisions leading to a realiable design highlighted.

4.2.1 Data Encoder

Data encoding includes a low power 12 bit, 11 channel analog-to-digital converter and a new small outline microcontroller that is compatible with the popular Intel 8051 industry standard. Both of these components are designed for low power operation. The ATMEL AT89C2051 processor is flash programmable. Software has been developed to encode the multi-channel analog data into a formatted data packet for modulating the RF transmitter. This includes error detection capability; if the receiver detects an error in a packet it is simply skipped and communication proceeds.

4.2.2 Radio Frequency Transmitter

The Motorola MC13176 is single chip solution for the RF transmitter. It is crystal controlled, very stable, and inexpensive. As part of HPOSS design, we have decided that each type of MBS-SS will have its own frequency (e.g., a right arm frequency, left arm frequency, etc.). This decision is also a consequence of human factors considerations associated with use. In actuality, a *frequency offset* will be mapped to the MBS-SS *type*. Different base frequencies will be employed for independent systems operating in the same vicinity. Spread-spectrum communication schemes are growing in popularity and were considered for HPOSS but ruled out because most module- or board-level products available are transceivers, i.e. they contain both receive and transmit subsystems. HPOSS requires only a transmit (from the human) capability; the added power consumption and size impinge upon desired performance characteristics.

4.2.3 Rechargeable Power Supply

The power supply consists of three integrated circuits produced by Maxim (performing recharging, regulation, and voltage doubling functions), a leader in low power electronic components. A nickel-cadmium battery has been used thus far as a matter of convenience (3.6V @ 300 mAH). Batteries with several times the energy density of standard nickel-cadmium cells are readily available permitting either size reduction or increased operational endurance. The electronics package is adaptable to a wide range of battery voltages and charge characteristics. Our goal is to achieve four hours of continuous operation on a single charge.

The charge control unit is designed to be incorporated into the SICU. The Maxim MAX 733 provides for a rapid recharge capability and can also be "programmed" to handle other newer rechargeable battery technologies (e.g., lithium, nickel-metal hydride).

4.3 HPOSS Base Unit

No Base Unit has been fabricated as of this writing under Phase I, as it has been viewed to be more straightforward than MBS-SS elements. Rather, a commercial receiver has been used for simple single-channel operation along with a desktop computer to accomplish decoding while various system architectures have been considered. In Phase II, we propose to employ the Base Unit structure shown in Figure 24. The design allows for the production of one, three, and five channel Base Units. A separate programmable receiver subsystem is required for each channel, since data must be received simultaneously in installations where more than one MBS-SS is employed (e.g., left and right arm types). The combination of a receiver with programmable frequency (to be set with the aid of a host-based HPOSS Set-up utility) and preset frequencies for each type of MBS-SS allows for operation without user confusion.

4.3.1 Multiple Channel Radio Frequency Receiver

The multiple channel receiver is formed simply by combining in the same unit 3 or 5 replications of the same receiver. A Motorola chipset including a programmable phase-locked loop will be employed (see Figure 24) that will allow programmable frequency selection in 5 kHz increments (approximately equal to worst-case bandwidth) over an approximately 902 - 920 MHz range. In constrast to the transmitter, neither power nor space requirements are crtical. With the design currently identified, a small but very sensitve RF subsystem can be realized. Performance required is readily available. At our current juncture in Phase I, we are now fabricating a prototype of the receiver that we intend to employ in Phase II.

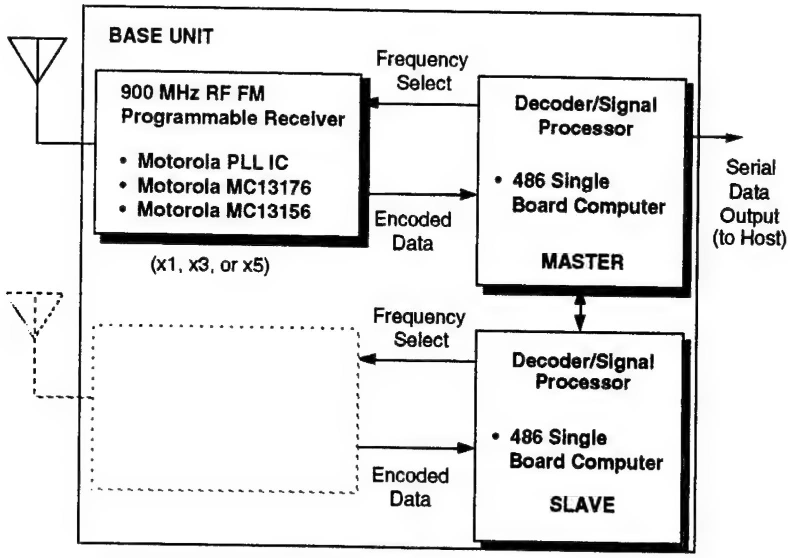


Figure 24. Functional units and design selections identified for realization of the HPOSS Base Unit.

4.3.2 Decoder and Digital Signal Processor

In Phase I, we constructed a single channel decoder which was used with a commercially available receiver to conduct feasibility tests. In Phase II, the problem of decoding and integrating data from multiple independent receivers will be tackled. The processing load is significant (see Section 3.3.3.3) for even a single channel system since one MBS-SS provides at least nine signals that must be processed to derive the appropriate joint angles. This application is ideally suited to use an embedded single board computer (e.g., a fast Intel 80486-based unit, which are commonly available). Thus, from a hardware perspective this component will be realized with "off-the-shelf" products.

Simple decoding algortihms have been developed and tested during Phase I. In Phase II, we intend to add error detection and correction to the this software (and encoding software) to the extent that the more limited processing power on the encoding side allows.

As Figure 24 illustrates, we have allowed for heavy processing demands by incorporating multiple single board computers in a "master-slave" arrangement within the architecture of a single Base Unit. A major effort associated with this component is the development software that combines data from multiple sensors to obtain joint angle information and then properly formats this information for all possible joints based on the data available. We address these issues in a separate section below.

4.3.3 Computation and Communication of Human Position and Orientation Parameters

Our objective to use standard conventions for both specifying joint angles and labeling joint angle data. This is a critical issue for managing data within the system as well as for communication with externally developed software applications (e.g., graphical tools, databases, etc.). HPOSS relies on an automated process to transform position data to joint angle data. This provides an extremely user-friendly system and places great data management demands on the overall design. The format invoked for both specifying and labeling the data can either add efficiency and expandability or severe limitations to this ability. While there are numerous examples of data specification and labeling formats within other systems, a review of various human-related

software applications revealed that no standards exist. Furthermore, case-specific approaches (e.g. knee only) are not designed to cover the total human or various domains. Because human structure, function, and performance are so inherently related in processing human movement, a single coding scheme is the logical approach to establishing a standard convention.

The complexity of the human architecture imposes an additional barrier for the development of a labeling standard. The development of a coding scheme therefore not only requires the ability to provide complete coverage of the total human system, but also requires a basis on which to reduce the system to its components at various levels (e.g., basic elements such as the knee extensor or a coalition of elements, such as a locomotor system, for higher level task analysis like gait performance). The Human Performance Institute Shorthand Code for the gross total human (Kondraske, 1992) was introduced to respond to this need and has been developing toward fulfillment of these requirements. Whereas there is no present standard and other methods are limited, we are confident that the use of this coding scheme is appropriate in the present context.

The HPI coding scheme is a simple ten character label with each character field corresponding to a specific aspect of the total joint description. Its format is based on the Elemental Resource Model (ERM) which provides systems approach to breaking down the human into basic elements. Specific to the needs of this project, the joint angle codes designate the specific joint (e.g., left elbow, right knee) and associated degree of freedom (e.g., flexion, abduction, external rotation), magnigude and direction of the angle and the particular biomechincal axis of rotation corresponding to the gimbal model used to specify the angles (see below). This code structure is consistant across the total human architecture and at various hierarchical levels. This provides the ability for software designers to scan specific fields for known codes to determine any aspect of the data from a structural, functional, or performance standpoint.

In addition to implementing a data coding standard, the format of the data itself is critical for efficient utilization in application software as well as data management. A joint angle data convention has been developed within HPI (Vasta and Kondraske. 1994, Standard conventions for kinematic and structural parameters for the "gross total human" link model, v2.6, HPI Technical Report 92-003R) that is generic across the human, well documented and readily available for processing in end user applications. Human musculoskeletal joints are modeled as gimbals (see Figure 1) and defined consistently across all joints. Here, the gimbal represents each joint as having a fixed center of rotation with three degrees of freedom. This assumption is sufficient for a large number of applications, in line with most assumptions regarding human measurement and movement, and provides for reduced measurement requirements (with respect to capturing a moving center of rotation). The gimbal axes are assigned to a specific degree of freedom, i.e., flextion/extension, abduction/adduction, or rotation, and labeled F, A, and R, accordingly. Therefore, regardless of the joint of application, each gimbal angle designates a specific type of joint rotation. The calculation of these angles is provided through the Euler angle representation procedure, with a specific Euler sequence corresponding to rotations about first the F-axis, then the A-axis, then the R-axis. This methodology is refered to the FAR angle representation and allows the determination of segment orientation and the mathematical manipulation of the associated coordinate systems for determining the joint angles. An example is provided below (Figure 25).

In the proposed Phase II project, HPOSS will be expected to provide time series joint angle data for the three degrees of freedom at each joint monitored. This data can then be used to drive graphical software, provide data for performance or biomechanical analysis, or for numerous other applications where real time human motion can be utilized. Regardless of the application, our goal is to provide a system that is both easy to use and provides a straightforward, readily applicable data output. The design of the physical aspects of the system therefore focuses on providing the end user with noncomplex components and few decisions regarding how they are implemented.

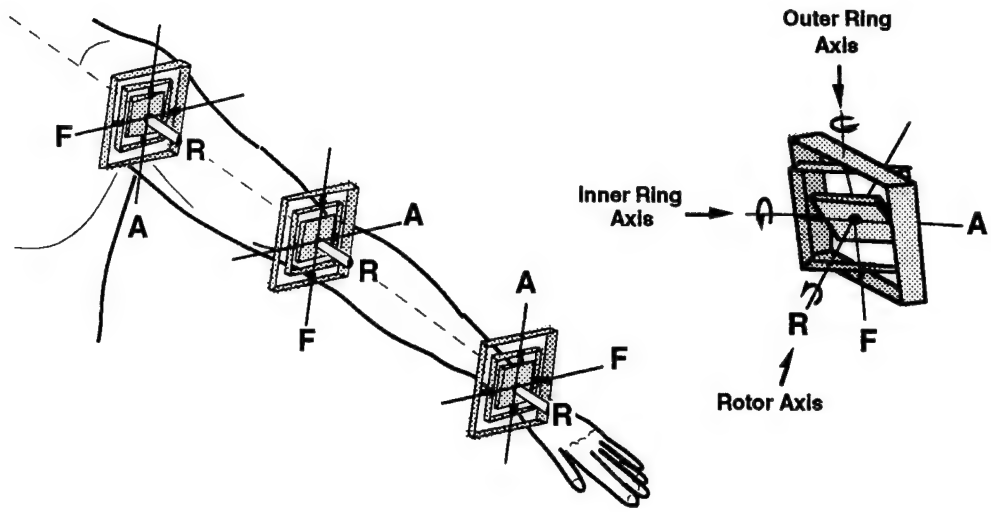


Figure 25. Gimbal model axes assignments shown as applied to the left arm.

Each Multiple Body Segment Sensor Subsystem (MBS-SS) will be uniquely designed for a specific body component (e.g., arm, leg or torso) and a specific body side. This approach not only reduces the number of separate components (i.e., straps, sensors, etc.) but also eliminates the possibility of arranging the components incorrectly, which would result in meaningless measurements. The flexibility resulting from body segment-specific units also allows certain human factors design considerations to be implemented. These include attachment bands that are sized for the designated body segment and conveniently positioned adjustments, allowing the wearer to put on the unit without assistance (see Figure 26).

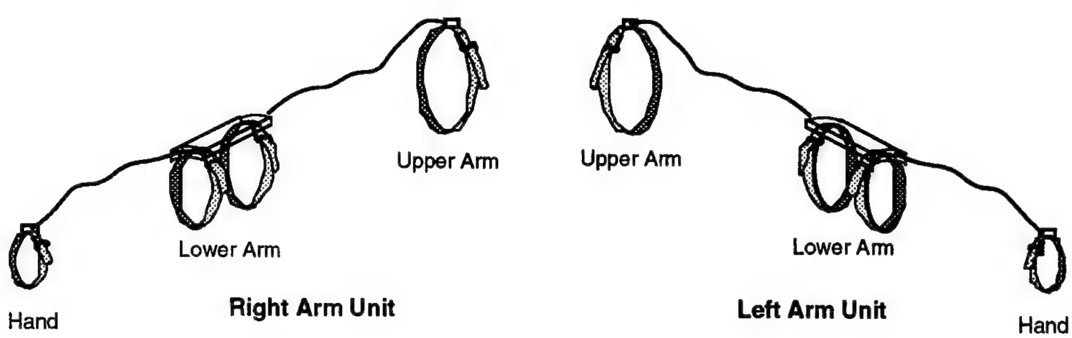


Figure 26. Two MBS-SSs designed as single components of HPOSS.

An additional benefit in a body segment-specific design results in automatic sensing of the number and type(s) of units in use. The user, therefore, would not need to instruct the system as to which units are being used or which joint angle is being measured. The hardware design will include a five-channel receiver, with one channel dedicated to each of the five types of goniometer units (right and left arm and leg and a torso unit). Each goniometer unit will transmit at a preset frequency (base plus the channel offset) that will be assigned to a specific channel. In situations where multiple sets of the same units are used simultaneously, as in the case of two or more human subjects, the additional receivers can be programed to a base frequency different from the other(s), matching the frequencies transmitted by the corresponding sets of MBS-SSs. Therefore, while the receivers are programmable (i.e., all receiver units are the same), MBS-SSs that transmit at different base frequencies must be obtained for such measurement situations.

The receiver unit obtains position data from the individual body segment sensors of the MBS-SS. This data is then transformed by the receiver unit into Euler angles, similar to the FAR representation described above. Thus, each body segment has an attached coordinate system offset from a world reference frame by a set of three gimbal angles. These gimbal angles will then be transfered to an external computer and matrix algebra will be employed to combine and manipulate the individual segment orientations into joint angle values in the form of FAR angles (see Figure 27). This is possible because a common frame of reference is used across sensors. An example of the process is provided below.

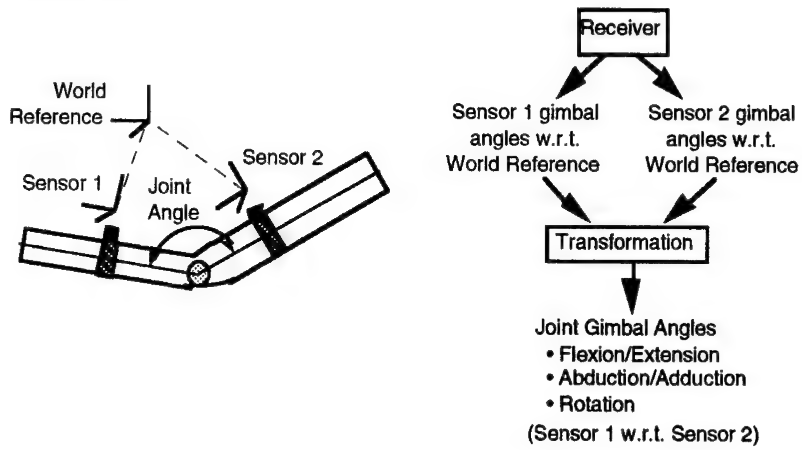


Figure 27. Individual sensor orientation data referenced to a world coordinate frame can be transformed to provide joint gimbal angles (FAR representation).

Euler angles are simply a well defined sequence of rotations about the axes of a coordinate system with respect to a reference frame. They describe the transformation of the moving coordinate system from an orientation initially aligned with the reference to an orientation after the rotations. This transformation can be represented as a three-by-three matrix which relates the moving and reference coordinate systems' basis vectors in Cartesian space. Thus, given the Cartesian coordinates of the basis vectors for two coordinate systems, A_1 (reference) and A_2 (moving), a transformation matrix, ${}^1T_2$, containing the associated Euler angles can be found using the equation

$$A_1 = {}^1T_2 \times A_2$$

Given another coordinate system, A_3, also referenced to A_1, such that

$$A_1 = {}^1T_3 \times A_3$$

then simple substitution will provide an equation relating A_3 (as the moving frame) to A_2 (as the reference in this case) through A_1 by

$${}^1T_2 \times A_2 = {}^1T_3 \times A_3$$

or

$$A_2 = {}^1T_2^{-1} \times {}^1T_3 \times A_3$$

where ${}^1T_2^{-1}$ is the inverse of ${}^1T_2$. The newly derived Euler angles of the combined transformation matrix, ${}^2T_3$

$${}^2T_3 = {}^1T_2^{-1} \times {}^1T_3$$

are then the angles relating the orientations of A_3 relative to A_2. In applying this example to HPOSS, joint angles in the form of gimbal angles of the FAR representation are readily calculated from the segement coordinate systems derived by the receiver unit. These angles are then tagged with the appropriate HPI shorthand code corresponding to the joint, degree of freedom, and direction (i.e., flexion or extension) and output for final processing.

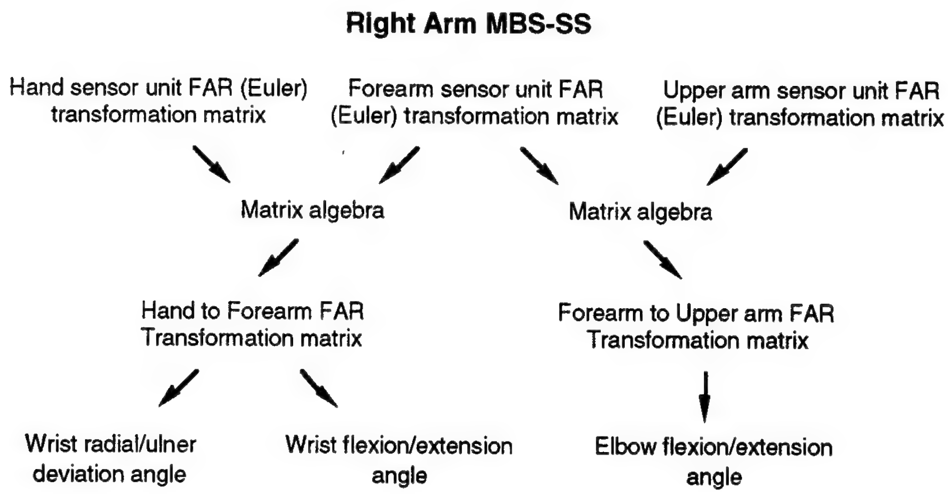


Figure 28. An example of the joint gimbal angle derivation process for the elbow and wrist.

Table 3. Summary of mapping between MBS-SS, body segments, joints, and their respective degrees of freedom (as defined under the HPI FAR system).

MBS-SS Type	Involved Body Segments	Involved Joints	Degrees of Freedom*
Right Arm	Right Upper Arm	Right Elbow	Flexion/Extension
	Right Forearm Right Hand	Right Wrist	Flexion/Extension Radial/Ulnar Deviation Pronation/Supination
Left Arm	Upper Left Arm	Left Elbow	Flexion/Extension
	Left Forearm Left Hand	Left Wrist	Flexion/Extension Radial/Ulnar Deviation Pronation/Supination
Right Leg	Right Thigh	Right Knee	Flexion/Extension
	Right Lower Leg Right Foot	Right Ankle	Plantar/Dorsi Flexion Inversion/Eversion Internal/External Rotation
Left Leg	Left Thigh	Left Knee	Flexion/Extension
	Left Lower Leg Left Foot	Left Ankle	Plantar/Dorsi Flexion Inversion/Eversion Internal/External Rotation
Torso	Cranium Thorax	Neck	Flexion/Extension Lateral Flexion (L/R) Rotation (L/R)
	Lumbar	Thoracolumbar	Flexion/Extension Lateral Flexion (L/R) Rotation (L/R)

*Joint angles determined from at least two segment sensor unit outputs

Software-based algebraic combination and manipulation of the segment angle data will then provide the joint angle values desired. in the FAR angle representation described above (see Figure 26). In general, given a known Euler representation and common reference across all segment coordinate frames, it is relatively easy to derive a transformation matrix that reverses and/or combines the Euler angles of any two coordinate systems. With respect to the sensor units of this project, each will have a representative coordinate system with a known orientation with respect to a common reference. This orientation will be the result of applying a specific Euler sequence, the FAR representation. Given this, the matrix representation of any two sensor orientations can be algebraically combined to result in a single transformation matrix that provides the gimbal angles relating the two.

In brief, FAR is a specific Euler angle representation, chosen because, when applied to the gimbal model, there are no restrictions as to the order of rotations (e.g., 10 degrees about the x-axis, then 25 degrees aboout the z-axis, then etc.). The point here is that while conditions such as sequence dependance is anticipated and routine in the analytical world, the opposite is true when measuring or communicating joint angles in real life situations. To better understand the issue, a breif explanation of the consequences of sequence dependence is now given. The orientation of one coordinate system (the moving system) with respsect to another (the reference system) can be defined in many ways, but all are specified by a sequence of individual rotations about the axes of one of the coordinate systems. Any three rotations involving at least two different axes completely defines a unique orientation in 3-space. The type of Euler representation utilized here prescribes consecutive rotations about the moving coordinate system axes. Thus, with the moving and reference coordinate systems initially aligned, the first rotation reorients the moving system and thus, the second rotation takes place about a newly positioned axis. Given this process, the desired orientation can be attained only if the specified sequence of rotations is followed for the given angles. It is relatively clear from this perspective that it becomes difficult to visualize how to rotate a coordinate systems about a newly positioned axis, especially after a second rotation. This is perhaps the primary reason why actual (clinical) joint angle measures have no dependency on one another and are done strictly within the anatomical planes. Here, then, lies the gap between the analytically derived joint angles and joint angles measures and communicated in many applied settings.

Applying the gimbal model to joints (human or artificial) provides a unique and simple bridge to this gap by forcing the Euler angle representation to map to the preset gimbal axes (which can be aligned with the body segment or anatomical planes) and provide sequence independent rotations. This occurs because each rotation about any axis of the gimbal model results in specific and unique changes in the orientation of the other axes. As can be visualized through in Figure 1, while rotation about the outer ring axis re-orients both the inner ring and rotor axes, rotation about either the inner ring or rotor axes has no effect on the outer ring axis orientation to the reference frame. Thus, this inherent relation between the gimbal axes directly maps to the Euler angle representation (i.e., the rotation sequence depends on the assignment of the gimbal axes, e.g., the first Euler rotation must occur about the outer ring axis, etc.). Because the physical architecture of the gimbal forces the axes to in relation to one another in this manner, when applied to the gimbal, the rotations are no longer sequence dependent, yet the angles of the rotations remain the same as those defined by the sequence-dependent Euler angle representation. The take-home point is that the mathematics that allow the determination and manipulation of coordinate system orientations in 3-space is directly applicable to the sequence independent measurement methods in the clinical world through the gimbal model. Furthermore, in assigning the gimbal axes to specific degrees of freedom at a joint, the Euler rotations then directly map to the clinical labels flexion/extension, abduction/adduction and rotations. Thus, to further bridge the gap between the analytical and clinical worlds, the Euler angle rotations assigned to the gimbal model are designated as the FAR angle representation.

Specifically within HPOSS, the gimbal model will also be used as the format for the position sensor data. For a single time sample, the sensor output (from the receiver) will consist of three gimbal angles for each degree of freedom. These angles describe the orientation of the sensor with respsect to a specified world reference system and correspond to the FAR angle representation scheme. Because the orientation of each sensor is known with respect to the same reference, it is then possible to determine their orientation with respect to each other, thus providing the joint angles desired. An example of the process is provided below for a hypothetical pair of sensors.

From the perspective of the receiving unit, the orientation of any sensor is provided in the form of FAR angle representation with respect to a world reference frame.

5.0 Plan for Commercialization of HPOSS Technology

Phase II efforts (or equivalent) will transition laboratory proven technologies (on the basis of results from Phase I and related concurrent projects) into commercially viable, completely specified, prototype products for an overall Human Position and Orientation Sensing System (HPOSS). These prototype products will include multiple multi-body segment sensing units (MBS-SUs), multi-channel reciever subsystems, computational software, and application interface software. Combinations of these products will be tested in relaistic application environments. If successful, Phase II will produce a set of products that can be easility operated and used in flexible configurations to optimally meet the needs identified applications that have a well-defined need for HPOSS capability. This will provide a firm basis for commercialization in Phase III.

5.1 Strategies

Phase III efforts will be focused on commercializing the HPOSS as a flexibly configurable and easy to use set of products that enable human interaction with and control of software and hardware devices in real-time using joint-angle and segment-position data directly from a user without line-of-sight limitations. We view the HPOSS as a major piece in establishing advanced virtual reality technology that supports more flexible, more natural, and higher bandwidth interaction and communication capabilities for enhanced human-computer interactivity. Our Phase III commercialization plan defines a multifaceted approach comprised of the three transfer stategies described in Table 4.

Table 4. Phase III HPOSS Commercialization Strategies

Strategy 1: Manufacture and sales to the Govenment.
The primary motivation for STTR project support by the government is to meet its' own needs. We have identified specific application programs in the Air Force and application areas in other government agencies that have a well-defined need for HPOSS. We will manufacture and sell configurations of HPOSS for these different application areas in accordance with government needs.
Strategy 2: Enhance existing HPM products
HPM Inc. has identified specific enhancements to selected human performance measurement products it currently manufactures and sells. Integration of HPOSS technology into existing products is expected to improve HPM's competitive advantage in selling these products.
Strategy 3: New product development.
HPOSS technology will enable HPM to expand its' services by offering new advanced products for private sector markets that satisfy current technology gaps in human and system performance related applications. This will expand HPM's customer base and range of applications.

5.2 Potential Applications

The capability that will be enabled by the HPOSS, (i.e., to reliably and cost-effectively measure and communicate human position and orientation in real-time) is of great benefit in improving the flexibility, bandwidth, and utility of the interaction between humans and computers in many applications in which the lack of this capability complicates and presents barriers to effective interaction. Applications for HPOSS technology exist in the military/government, medical, industry, and recreation sectors as listed in Table 5.

Table 5. HPOSS Applications by Major Sector

Military and Government
• Advanced command and control stations • Teleoperation of robots and robotic vehicles, airborne re-fueling, exoskeletons • High-fidelity interactive training and simulation • Scientific visualization
Medical
• Human-computer interfaces for persons with disabilities • Rehabilitation (e.g., motion analysis, performance measurement, biofeedback during therapy) • Computer-assisted training for surgery • Artificial proprioception for use in assistive device technology and robotics
Industry
• High-fidelity human interfaces for control of complex systems • Human-computer interfaces for persons with disabilities • Computer-assisted training (e.g. maintenance) • Artificial proprioception for use in assistive device technology and robotics
Recreation
• High-fidelity interactive games • Artificial proprioception for assistive sports devices

Success in Phase II will result in significant new capabilities for commercial applications. Universities with programs in the following areas are expected to form a major commercial application market segment:

- Human factors/industrial engineering programs: work in both medical/sports and military/industrial arenas
- Bioengineering programs: rehabilitation, biomechanics, functional electric stimulation, etc.
- Kinesiology programs: sports and medical
- Gait laboratories: usually supported by multi-disciplinary teams
- Physical therapy programs
- Robotics programs (human-workstation designs and interfaces)

Use in these academic environments will seed commercial applications in the respective areas in which former students practice professionally. Target markets within the practitioner arena are:

- Rehabilitation centers
- Occupational medicine centers
- Industrial ergonomic consulting firms
- Medium to large size companies (military and non-military) with internal ergonomic or human factors groups
- Sport study/training centers (e.g. US Olympic Centers, etc.)

6.0 KEY PERSONNEL

This section briefly describes the team involved in the HPOSS project to date (e.g., Phase I), as well as those who are anticipated to join the effort in the next phase of work.

Dr. Kenneth J. Maxwell, Principal Investigator. Dr. Maxwell brings experience in human factors, cognitive psychology, and HCI analysis, design, and evaluation to the program.

Mr. Paul J. Vasta M.S. His primary responsibilities included MBS-SS development and test, and developemnt of data transformation methods. Mr. Vasta has an M.S. degree in Electrical Engineering. He is a doctoral candidate in Biomedical Engineering at UT Arlington (graduation expected 12/95) and has been a Graduate Research Assistant at the Human Performance Institute for four years. During this time he has made significant contributions to numerous projects including a method for inferrential task analysis and performance assessment, the development of standard conventions for coding human structural and performance data and specifying musculoskeletal joint angles, and the design of a computer aided design software package for human-machine-task performance analysis (HMT-CAD) as well as the development of supporting software modules and tools. His current doctoral research involves the development and assesment of an approach to multidimensional musculoskeletal performance capacity estimation. It is anticipated that he will join HPM upon completion of his graduate studies.

Charles T. Hixon, B.S.,Engineer. His primary responsibilities included fabrication and test of HPOSS subsystems, especially Sensor Units. Mr. Hixon graduated with a B.S. in electrical engineering from the University of Texas at Arlington in 1992. Since that time, he has been employed as the chief product engineer at HPM, Inc. and has been responsible for a wide-range of activities including analog and digital electronics design, microcontroller software (assembly), and system application software development. He has personally managed small scale production of five hardware and software products.

Dr. George V. Kondraske, UT Arlington, University subcontract. Chief architect of HPOSS technology; heads the efforts conducted by the HPI. Dr. Kondraske brings extensive experience in instrumentation development, technology transfer, and system performance measurement to the program.

Mr. Phillip J. Fiedler, M.S., Graduate Research Assistant (GRA). His responsibilities include sensor subsystem development and test, and data standards development. Mr. Fiedler has a Masters degree in Electrical Engineering and is currently a Ph.D. student in the Electrical Engineering Department at UT Arlington, and a GRA for HPI. In this capacity he has been investigating inertial sensor technology, and more specifically, simulations for position and orientation measurement designs.

Mr. John Stevens, UT Arlington, HPI Staff, Electronics Technician/Instrument Maker. Mr. Stevens, who has worked with Dr. Kondraske for thirteen consecutive years, fabricated numerous test circuits and jigs required for prototyping and evaluation of all subsystems.

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